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# *The Journal of*
# THE ROYAL AERONAUTICAL SOCIETY

CONTENTS APRIL 1951

CLEAR AIR TURBULENCE OVER EUROPE
*G. S. HISLOP, Ph.D., B.Sc., A.R.T.C., A.F.R.Ae.S., M.I.Mech.E.*

MEASUREMENT OF JET ENGINE THRUST
*BENGT JAKOBSSON, Dr.Sc.(Eng.), A.F.R.Ae.S.*

86th ANNUAL REPORT OF COUNCIL 1950-1951

REVIEWS

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# Getting Cracking . . .

WE all know about oil. We've seen it on the movies. There's this fellow whatsisname—a Gary Cooper type—weary and lean-jawed, and there's a blonde in a check shirt in the offing. And one fine technicoloured day, after years and years of failure, privation and squalor . . . whoops ! Up she comes. There he is, our hero—his rows of white teeth gleaming in blackened, oil-soaked features—running for a marriage licence. That's oil.

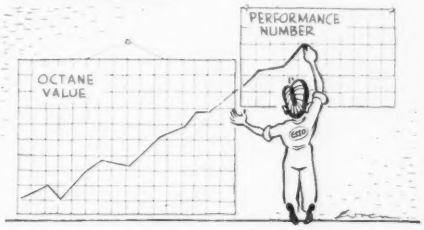
Well, isn't it ? They pump the stuff from Nature's underground reservoirs, label it petrol, gasoline or juice and bury it again under garages and airports. They do the same with gold, don't they ? Unearth it in South Africa and bury it at great expense on the other side of the world. Right ?

Not quite ; we're forgetting something. We're forgetting that crude oil is crude. We're forgetting chewing gum, candles, insecticides, explosives, inks, paints, synthetic rubber, diesel fuels, asphalt, lubricating oils, salves, creams, ointments, tractor fuels, jet fuels . . . *motor spirit*, AVIATION FUELS . . . and a thousand other things. No, the oil industry isn't merely a super transport organisation charged with the task of moving oil

from well to consumer by means of fine fleets of tankers, tank cars and pipe-lines : it's a dozen industries in one, and its chief job is to convert crude oils into fuels of maximum efficiency for every type of engine.

Think of an octane number . . . double it . . . double it again. That's roughly what the industry's been up to these last few years. It has recently produced aviation fuels so high in anti-knock value that they ran right off the octane* scale and met up with a new yardstick, PN or Performance Number. And the work of tailoring fuels to fit engines and engines to fit fuels goes on, and on. The engineers, scientists, technologists and physicists of the oil industry sit in their laboratories and think of a performance number . . . double it. . . .

No, it's not just a matter of emptying wells and filling pumps.




What is the oil industry doing in Britain ? Answer—the biggest job in its history. What are ESSO doing ? Answer—their biggest job ever. In this country we're now using about seventeen million tons of oil products a year. Nearly all of this oil is imported—from the Caribbean and increasingly from the Middle East—and half of it was refined overseas. But soon, two years from now, when the industry's £125,000,000 building programme has been largely completed, the country will be independent of refineries abroad.

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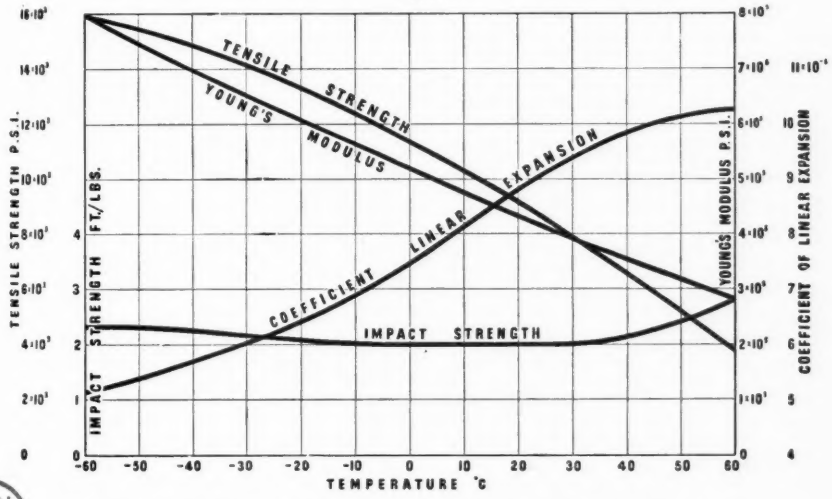


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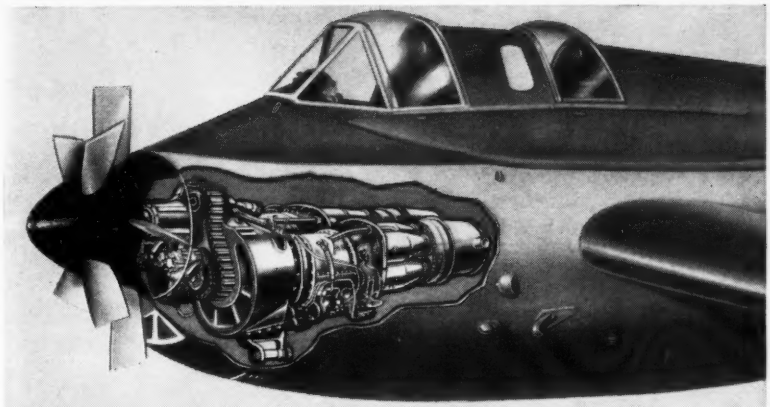

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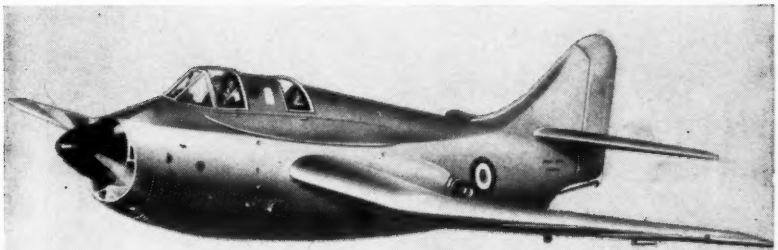

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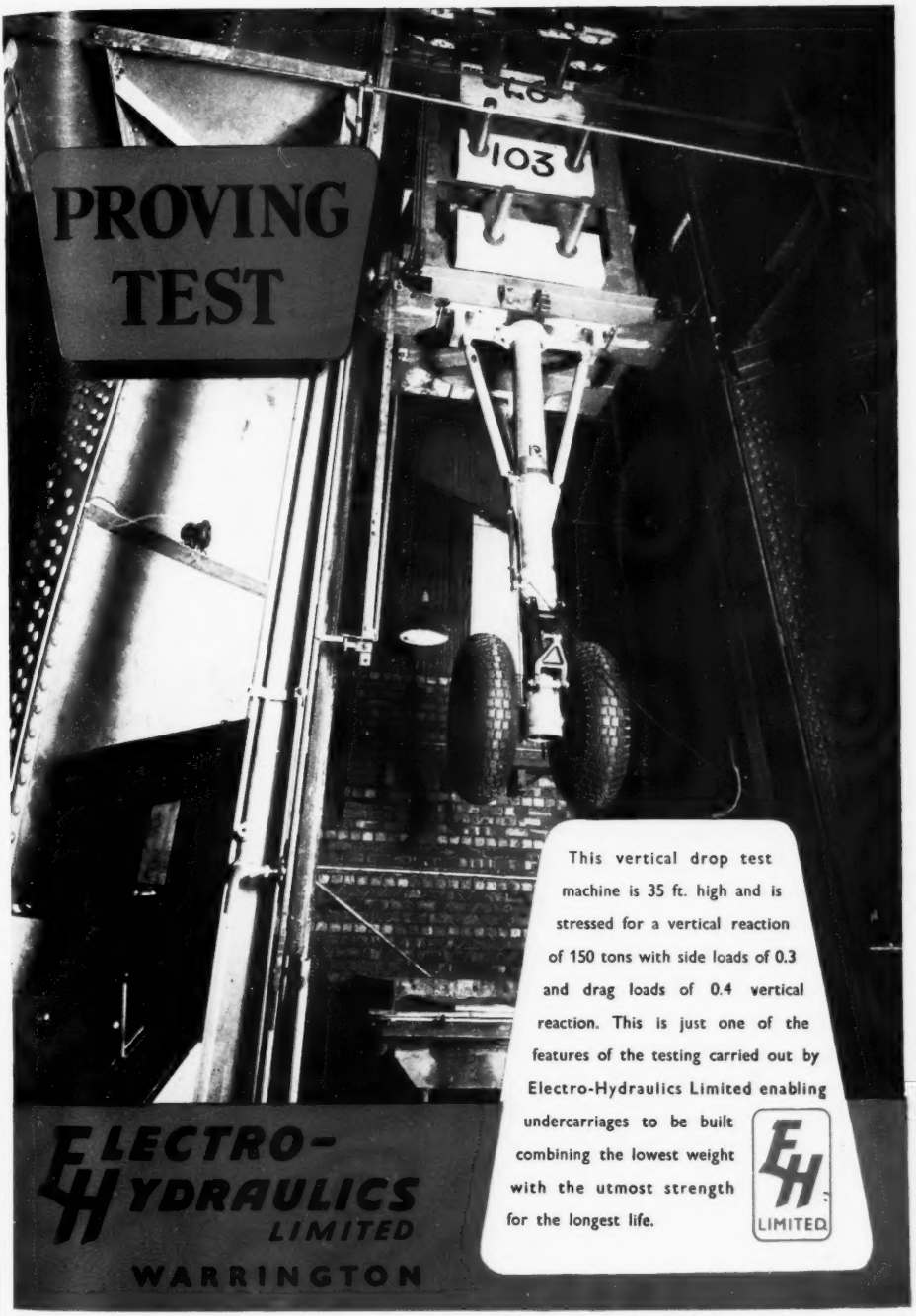
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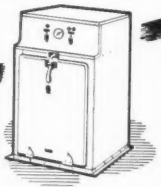

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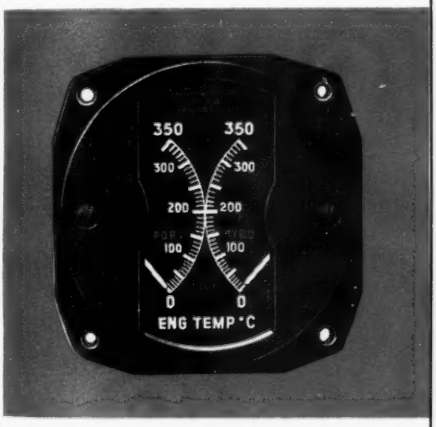


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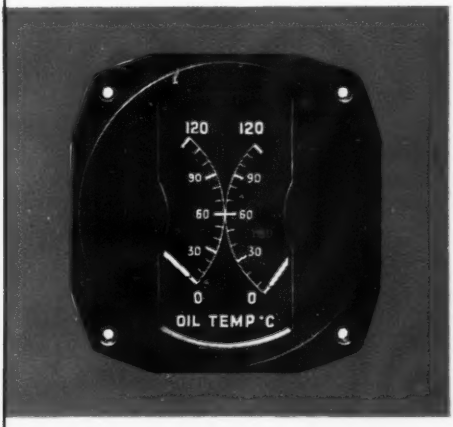


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CONTENTS

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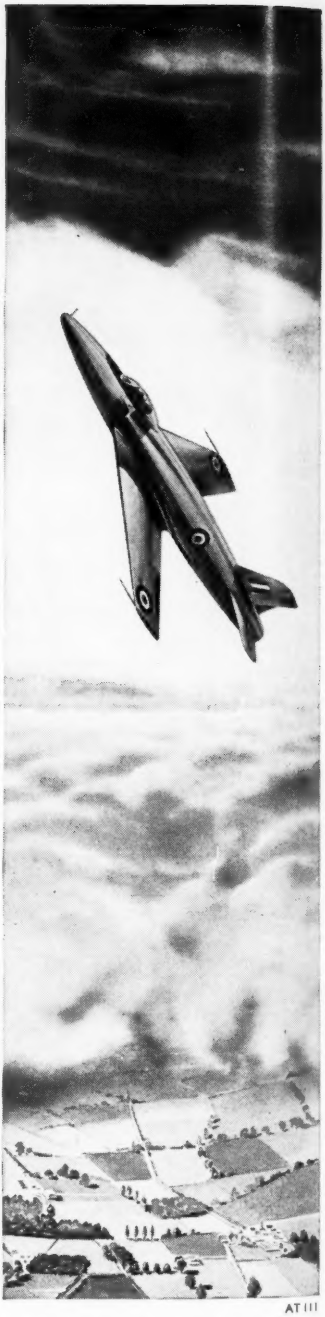

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# CLEAR AIR TURBULENCE OVER EUROPE

by

G. S. HISLOP, Ph.D., B.Sc., A.R.T.C., A.F.R.Ae.S., M.I.Mech.E.

A joint meeting of the Royal Aeronautical Society and the Royal Meteorological Society was held on 14th December 1950 at the Institution of Civil Engineers, Great George Street, London, S.W.1, at which the 814th Lecture to be delivered before the Royal Aeronautical Society was given by Dr. G. S. Hislop. Major G. P. Bulman, C.B.E., F.R.Ae.S., presided at the meeting and after welcoming the members of the Royal Meteorological Society and especially their Secretary, Professor Sheppard, and expressing his regret at the absence in America of the President of the Royal Meteorological Society, Sir Robert Watson Watt, he introduced the Lecturer, G. S. Hislop, Ph.D., B.Sc., A.R.T.C., A.F.R.Ae.S., M.I.Mech.E., Senior Assistant to the Controller of Research and Special Development, British European Airways Corporation.

## 1. INTRODUCTION

When the problem of operating jet-propelled civil aircraft first began to be studied seriously a few years ago, it became clear that there were many new problems to be faced and solved if the venture to high altitude were to be successful. There were the problems of pressurisation, air conditioning, cruise control, meteorological forecasting, air traffic control—to quote only a few. Another was that of encountering turbulence in clear air—and hence without warning. Such occurrences had been reported occasionally by military pilots during the 1939-45 War, but the young, fit crew members of a military aircraft, probably strapped in their seats, are vastly different from the average passenger clientele of a civil operator. Of all ages and physical conditions, they could not be expected to accept with equanimity a sudden violent shaking of the aircraft in clear blue skies "far above the weather." Furthermore, those same passengers could express their disapproval of untoward occurrences by simply changing their future mode of travel. These considerations, coupled with one or two experiences reported from the U.S.A. involving Constellation aircraft, emphasised the need for a proper investigation of the matter.

One of the difficulties was that virtually nothing was known about the problem, except that the turbulence was rather patchy and possibly not very frequent. While this did not give much guidance, it emphasised the importance of reliable information, not only from the passenger comfort aspect, which was of most importance to the operators—but from the structural and meteorological aspects also. It is a fact that the structural strength of high speed civil aircraft is largely governed by the gust case and ability to withstand the heaviest turbulence is vital. Yet the present gust standards, which are agreed both nationally and internationally, are founded on relatively few observations at high altitude, thus accentuating the importance of obtaining more detailed information.

It was these aspects of the matter which in 1946 led N. E. Rowe, Controller of Research and Special Developments, British European Airways, to suggest to the Ministry of Supply that a research project, to be operated and directed by the Corporation, should be initiated with the following aims:—

(*i*) To determine the probable frequency and extent of turbulent areas in clear air, and the magnitude of the associated gust velocities.

(*ii*) To determine the causes and characteristics of this turbulence.

(*iii*) To provide a basis upon which a forecasting system could be founded.

The advantage of an airline being responsible for such a project as this is twofold. Firstly, airlines facing the problem of

passenger operation at high altitudes are better able to appreciate the significance of this particular aspect. Secondly, the organisation of overseas flights is a relatively simple matter for an airline with an overseas network, as the aircraft and crew and all the usual formalities can be dealt with easily.

Naturally the proposal implied that the investigation would be made over the normal territory of the Corporation, *i.e.* Europe and the United Kingdom, although the possibility that flights would be made to other areas was always borne in mind.

Recognising the importance of the work the Ministry of Supply agreed to supply the aircraft and to support the project financially; full co-operation was promised from the Meteorological Office, the Air Registration Board, and the Ministry of Civil Aviation.

The chosen aircraft (two Mosquito PR 34s) were received from the Ministry of Supply in September 1947, and work was begun at the base of the Corporation's maintenance sub-contractors, the Department of Flight, College of Aeronautics, Cranfield, to bring them up to the standard required for the issue of a Certificate of Airworthiness and to install the necessary instruments. The first converted aircraft flew in January 1948 and after a series of calibration tests and proving flights, settled down to research flying proper in April 1948. The second aircraft became available in June 1948 and from then onwards the work continued until January 1950, although a number of interruptions due to unserviceability, modifications, crew illness, and so on, were encountered. The work was terminated at this date, largely as a result of the financial retrenchment following the devaluation crisis of early Autumn 1949.

This paper describes briefly the organisation and equipment used in the project, and gives the main structural and meteorological results, their implications and lessons in more detail.

## *NOTATION*

$U_e$ = equivalent vertical gust velocity, equivalent air speed (ft./sec.)
$w$ = wing loading (lb./ft.$^2$)
$\Delta n$ = increment in acceleration, in $g$ units
$V_1$ = equivalent air speed (ft./sec.)
$\rho_0$ = standard air density at sea level (slugs/ft.$^3$)
$K$ = alleviation factor = $0.8 - 1{\cdot}6/w_4^3$
$a$ = slope of lift curve (4.05 for Mosquito)
$V$ = wind speed (ft./sec.)
$z$ = vertical axis
$s$ = horizontal axis
$T$ = ambient air temperature, °C absolute
$\Gamma$ = adiabatic lapse rate
$g$ = acceleration due to gravity
$\Omega$ = angular velocity of earth, radians/sec
$\phi$ = latitude

*In Figure 1*

$n_s$ = number of gusts of given magnitude from a *sample* record
$d_s$ = distance covered during a sample
$D_s$ = distance flown on one "leg" of the sawtooth flight plan (*e.g. AB* or *CD* in Fig. 1).
$n_r$ = number of gusts of given magnitude recorded in the turbulent area
$d_r$ = distance flown in turbulent area while accelerometer record is being taken
$D_r$ = horizontal extent of turbulent area
$N$ = equivalent number of gusts of given magnitude encountered during flight in this height band

## 2. EQUIPMENT AND ORGANISATION

### 2.1. General

It was decided initially that the unit to be set up for this investigation should be as small as possible, and that any instrumentation employed should be as simple as possible. Results might thus be obtained fairly quickly and cheaply to indicate whether the investigation was proceeding on the right lines. Later events showed that a unit of two aircraft and one crew (the initial complement) was rather too small to ensure continuous flying and that three aircraft and two crews would have been much better.

### 2.2. Aircraft

Two PR Mk. 34 Mosquito aircraft with Merlin 114A engines, converted from military to civil standards, were flown under the registration letters G-AJZE and G-AJZF. The Certificates of Airworthiness issued in the Special Category permitted them to be flown at an all-up weight of 22,000 lb., but the normal take-off weight was about 21,500 lb., when carrying 739 gallons of fuel.

### 2.3. Base

The aircraft and crews were based at the College of Aeronautics, Cranfield, Bedford-

shire, the Flight Department of the College being responsible to British European Airways for the overhaul, maintenance and servicing of the aircraft. Spares and most of the ground equipment were provided through the normal R.A.F. Maintenance Unit channels, special arrangements having been made to this end.

### 2.4. Crew

It was found possible to recruit fully experienced Mosquito pilots from within the Corporation, but for the radio officer/navigators outside recruitment was necessary. Initially, it was considered that one crew would be able to deal with the 500-600 hours per annum which it was thought could be achieved with two aircraft. It became clear in the summer of 1948, when the target rate was reached for a short period, that the strain of this work was greater than imagined. The precise flying called for, the necessity to breathe oxygen for long periods, and the low pressure to which the body was exposed, coupled with the rather marginal stability characteristics of the Mosquito, especially at high altitude, all threw a great burden on the pilot. As no automatic pilot is fitted to Mosquito aircraft he could not even be released from the task of actual flying during any part of the flight.

The navigator-cum-radio operator was called upon to navigate the aircraft to a most difficult flight plan which often involved wide changes in wind speed and direction with the progressive variation in height (*see* Section 3). As GEE cover was available for only about half of each overseas voyage, great care and attention had to be given to DR navigation. In addition, he had to interrupt his navigation and radio work to observe the ambient air temperature at frequent intervals. All these factors made the crew's task a very heavy one from both the physical and psychological aspects.

As a result of the pilot's illness during the winter of 1948/49 a second crew was recruited, and when it became fully operational in May 1949 the improvement was marked. The restriction on flying rate then switched to the aircraft, and it was obvious that a third aircraft was necessary to maintain a steady flying rate in face of the frequent periodic inspections, random defects, and the flow of modifications to which this type of aircraft is subject.

### 2.5. Instruments

The fairly common technique of using the aircraft to carry recording accelerometers, the results from which are converted to the corresponding vertical gust velocities, was employed in this project. No attempt was made to measure horizontal gust velocities.

(*i*) The main recording accelerometer was a Peravia type XR 144. This instrument is clockwork-driven and remotely controlled by electrical means. The movement of a spring suspended mass, having a natural frequency of about 12 c.p.s. is recorded on a moving paper strip set to run at 2 mm. per second. The record is obtained in the form of a series of tiny punches on waxed paper, the rate of punching being 10 per second while the running time is approximately 40 minutes.

No trouble was encountered with the two instruments of this type which were employed throughout the two years of operation.

(*ii*) In order to obtain data concerning the rate of build up of acceleration a Barnes type B recording accelerometer was fitted. For a variety of reasons, mostly mechanical or electrical troubles, few satisfactory records were obtained either from this instrument or a modified version fitted at later stage.

(*iii*) *A V-g* recorder was installed at the request of the Royal Aircraft Establishment, Farnborough, and all the records from this instrument were dealt with by the R.A.E. No data derived from the *V-g* recorder have been used in this paper.

(*iv*) The ambient air temperature was measured on a Meteorological Office balanced bridge thermometer, Mk. Ib, which is reliable and accurate to $\frac{1}{2}$°C.

(*v*) Kent flowmeters of the "gallons gone" type were fitted to give a reliable indication of the fuel available at any stage of a flight; they also enabled the wing loading at any time to be determined with reasonable accuracy.

The recording accelerometers were under the control of the pilot, who also noted the fuel consumed, while the navigator/radio operator was responsible for taking the necessary readings of air temperature.

### 2.6. Radio

To permit full freedom of operation over Europe the following radio and radar navigation and communication equipment was installed:—

(*i*) VHF, type TR.1430.
(*ii*) HF, type SCR.274N.
(*iii*) Beam Approach, type R.1598/1599.
(*iv*) GEE Mk. II, type ARI.5083.
(*v*) ADF, type Marconi AD.7092.
(*vi*) Inter-communication, Bendix 3611 B.

The ADF equipment was not fitted until mid-1949, but there was no doubt that it was of the greatest assistance, especially when the aircraft was outside GEE cover, as was usual for approximately half the distance on each overseas flight.

### 2.7. Customs

In the absence of any special arrangements during the first year or so, all Customs clearances were made at London Airport, but with the help of the Ministry of Civil Aviation and the Customs authorities "on call" facilities were eventually provided at Cranfield. This proved a great boon and eased the strain on the crews considerably.

### 2.8. Flying effort

During the twenty-five months from January 1948 to January 1950 inclusive, a total of 680 hours was flown by the aircraft. Of this time some 124 hours were on test flying, positioning flights and so on. The remaining 556 hours were spent on gust research work proper, and have been termed "voyage hours" (each research flight was termed a voyage). Six out of a total of 187 voyages were rendered abortive or partly so, by defects occurring while airborne, (*e.g.* four complete engine failures took place). The voyage times quoted are "chock to chock" time so that the actual time flown above the lowest altitude at which observations were made totalled approximately 320 hours. The corresponding distance flown has been determined from the navigational log and is 92,300 statute miles.

## 3. FLIGHT TECHNIQUE

At the outset so little was known about this phenomenon of clear air turbulence that the programme was based on making as many sampling flights as possible over the European area. The destinations were chosen so as to cover a wide variety of terrain and weather conditions, while the flight plan adopted as a general routine was such as to give the maximum chance of finding any turbulence existing over the chosen route. This flight plan was of a sawtooth pattern in that the aircraft took off, climbed to about 37,000 ft., descended to 20,000 ft., climed to 37,000 ft., and descended to 20,000 ft. and so on until the destination was reached. Usually three such "sawteeth" would be flown on an overseas flight of normal length. (*See* Fig. 1).

Overseas flights were usually of about 1,000 miles range from Cranfield and were made to places such as Lisbon, Gibraltar, Rome, Stockholm, where B.E.A. stations existed. Flights were also made over the United Kingdom, and one was made to Iceland where the necessary arrangements were made by B.O.A.C.

The approximate track of all voyages is given in Fig. 2, which also shows the approximate centre of each turbulent area encountered. (The preponderance of flights to Lisbon is due to this route being especially suitable as a training route.)

By running the Peravia accelerometer for about one minute and observing the air temperature each time the aircraft passed through 20,000 ft., 25,000 ft., 30,000 ft., and so on, a sample of the state of the atmosphere at those heights was obtained. On encountering turbulence (defined as giving accelerations of at least $\pm 0.2g$ from the $+1g$ datum) the sawtooth pattern was abandoned, and a search instituted. Turbulent areas giving bumps $< \pm 0.2g$ were not investigated, as they were considered of minor importance in civil aviation, and also, because investigation of the more frequent cases of lower accelerations would probably have been done at the expense of the more important areas with greater turbulence.

A search aimed at determining:—

(*i*) the thickness of the turbulent layer.
(*ii*) the temperature lapse rate for some thousands of feet above, through, and below the layer.
(*iii*) a sample of the turbulence in the layer.
(*iv*) the approximate horizontal extent of the layer.
(*v*) the temperature gradient in the horizontal (added September 1949).

Partly for operational reasons and partly to increase the range of altitude covered, the

upper and lower limits of the sawtooth flight plan were altered in April 1949 to 35,000 and 15,000 ft. respectively.

In general the flight technique proved very satisfactory, and good results attended its use, twenty cases of clear air turbulence having been found on nineteen voyages during the period. Basic details of these "positive" results are given in Table I.

## 4. RESULTS—GENERAL COMMENTS

The results fell into two broad categories:

(*i*) *Statistical*—Measurement of accelerations and hence analysis of gust frequencies.

(*ii*) *Meteorological*—Determination of local conditions and analysis of general weather situation.

Results in the first category were derived entirely from the data obtained on each flight in the form of accelerometer recordings, and related observations of speed, height, fuel consumed and so on. On the other hand, the meteorological observations from a flight consisted mainly of the temperature lapse rate and the dimensions of a given turbulent layer, coupled with general remarks from the pilot on the prevailing meteorological conditions. Subsequently more detailed information on the weather situation, upper air data and so on, became available from the daily weather reports of the Meteorological Office. Some one to two per cent. of the recording time was actually in thin, high cloud of the cirrus, alto-stratus and alto-cumulus varieties, in which a pilot would not normally expect turbulence. For the purpose of this investigation such cloud was treated as clear air. A few observations taken in the vicinity of cumulo-nimbus clouds have been disregarded.

It is proposed first to describe and analyse the results from these two categories separately and then pass on to a discussion of their inter-relationship.

## 5. STATISTICAL RESULTS

### 5.1. Analysis of accelerometer records

The broad aim of the analysis was to present the information in the form of the number of positive and negative gusts of a given severity likely to be met by an aircraft flying within a given height band for a certain distance. As mentioned in Section 3

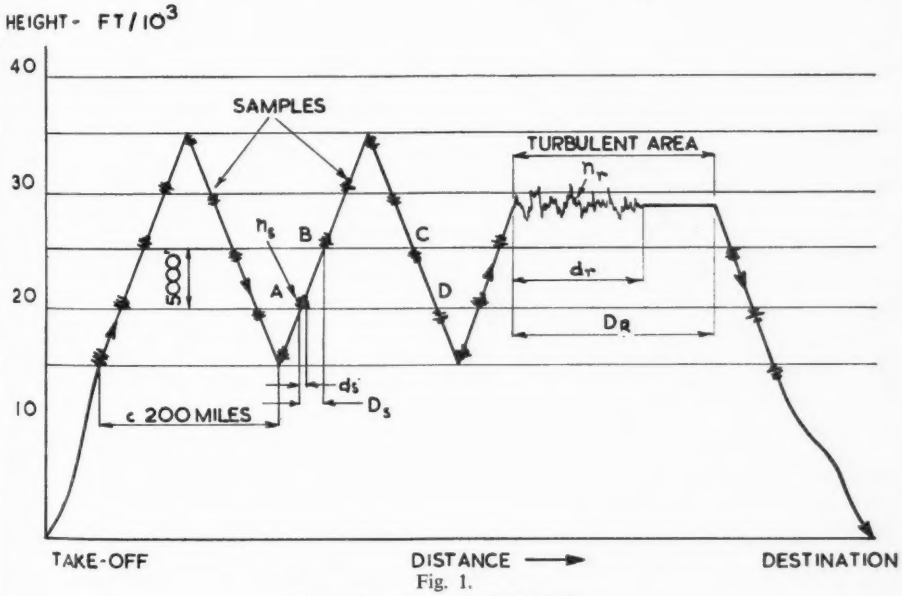


Fig. 1.
Illustration of saw-tooth flight plan.

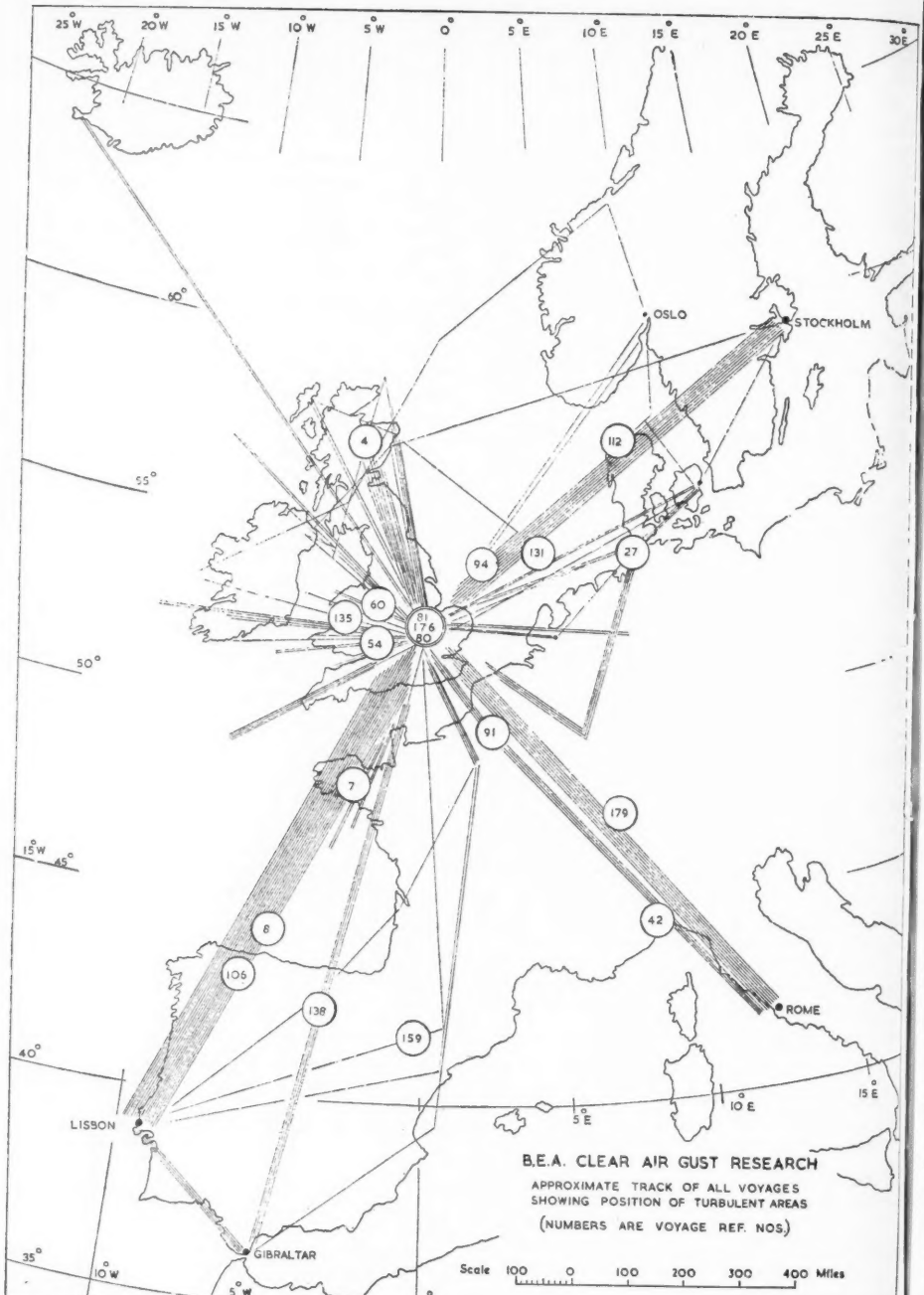
25°W
20°W
15°W
10°W
5°W
0°
5°E
10°E
15°E
20°E
25°E
30°E
60°
55°
50°
45°
40°
35°
15°W
10°W
5°W
5°E
10°E
15°E
OSLO
STOCKHOLM
4
112
94
131
27
60
135
81
176
80
54
91
7
179
42
8
106
138
159
ROME
LISSON
GIBRALTAR
B.E.A. CLEAR AIR GUST RESEARCH
APPROXIMATE TRACK OF ALL VOYAGES
SHOWING POSITION OF TURBULENT AREAS
(NUMBERS ARE VOYAGE REF. NOS.)
Scale 100 0 100 200 300 400 Miles

Fig. 2.

the accelerometer records fall into two classes:

(*i*) Sample recordings around fixed heights, of magnitudes $< \pm 0.2g$.

(*ii*) Search recordings in a turbulent area, of *all* magnitudes.

The problem is thus to combine these two classes to enable the data to be presented as for level flight within various height bands.

The choice of the best method for analysing accelerometer records in order to present the full information contained in the records in a simple numerical form is not particularly easy, because many factors must be taken into account[18]. In this instance it was decided to count the number of acceleration peaks lying within various bands of acceleration of "width" 0.1*g*. The bands chosen were 1.1*g* to 1.2*g*, 1.2*g* to 1.3*g*, and so on in the "positive *g*" sense, and 0.9*g* to 0.8*g*, 0.8*g* to 0.7*g*, and so on in the "negative *g*" sense. This process was carried out for each 5,000 ft. height band, *i.e.* 15,000 to 20,000 ft., 20,000 to 25,000 ft., and so on.

It was found that clear air turbulence nearly always gave a record consisting of positive and negative accelerations following one another in succession and this had the effect of nearly always giving maximum peaks in the "positive *g*" sense and minimum troughs in the "negative *g*" sense. There were a few occasions when the analyst had to exercise his discretion and decide, for example, whether a protracted positive acceleration was due to genuine turbulence or to the pilot inadvertently applying elevator control. On the whole, however, the analytical process was fairly straightforward.

After counting the various peaks the next step was to convert the accelerations to equivalent vertical gust velocities using the orthodox formula*

$$U_e = \frac{2w\,\Delta n}{\rho_0 K a V_i} \quad . \quad . \quad (1)$$

(*See* Notation).

*It is important to note that many American reports use a definition of $K$ which is different from that given by the British Civil Airworthiness Requirements. For a wing loading of 44 lb./ft.$^2$ representative of the Mosquito—the American value is about 1.18 while the British factor is about 0.7. This point must be watched in any comparisons of U.K. and U.S. gust data. All gust data in this paper are based on the British definition of $K$.

These equivalent vertical gust velocities were then separated into various height bands of 5,000 ft. thickness, *e.g.* 20,000 ft. to 25,000 ft., the sample at 20,000 ft. being taken as representative of that layer.

Referring to the typical flight plan illustrated in Fig. 1, and considering *one chosen* height band,

$$N = \Sigma n_s \frac{D_s}{d_s} + n_r \frac{D_r}{d_r} . \quad . \quad (2)$$

This process was repeated for various gust magnitudes (both positive and negative separately) for various height bands covering the range of altitude. The results are given in Table II. From this table the results have been cast in such a way as to show

(*a*) Miles to fly to meet a gust of a given magnitude, or greater. (Figs. 3 and 5.)

(*b*) Relative frequency of occurrence of gusts of various magnitudes. (Fig. 4.)

### 5.2. Discussion of Statistical Results

Before actually discussing the results in detail it seems appropriate to set out the characteristics of clear air turbulence as reported by the crews, and indeed by almost anyone who has experienced this phenomenon.

First of all is the absence of visual warning of its presence. It also appears that the bumps follow one another much faster than in convective type cloud, giving the feeling of "being in a fast car suddenly running over a series of deep unseen ruts in a road"—to quote one of the pilots. This "hammering" impression has been borne out by all the crews who have experienced the turbulence, but unfortunately it can neither be confirmed nor denied from the available records.

No height change takes place during a traverse, probably because positive and negative accelerations generally follow each other in succession. It is also noteworthy that on only two occasions was wing dropping ever reported in this type of turbulence, thus suggesting that the eddies usually encountered were considerably larger than the wing span of the aircraft.

Reference to Table I shows turbulence occurring in patches of various thicknesses, but averaging around 3,000 ft., and of various horizontal extents, although a representative dimension is 50 to 100 miles. It is clear, therefore, that most of the time the

## TABLE I. DETAILS OF "POSITIVE" VOYAGES

| *Ref. No. Locality Date* | *Position Time, G.M.T.* | *Horizontal Extent* | *Vertical extent (feet)* | *Maximum acceleration equivalent gust velocity* | *Tropopause height (feet)* | *Features of high level chart* | *Temp. lapse rate* $\frac{\partial T}{\partial z}$ | *Wind shear in* *Vertical* $\frac{\partial V}{\partial z}$ | *H'zontal* $\frac{\partial V}{\partial s}$ | *Assoc'd. with polar front* | *Remarks* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| VR 4<br>Braemar<br>6.4.48 | 57.00N<br>03.20W<br>13.20 | 50 miles | 18,500<br>to<br>20,000 | 0.55*g*<br>19 ft./sec. | 32,000<br>not<br>associated | Jet<br>stream | Stable<br>part<br>isothermal | High | High | On<br>p.f. | On jet stream<br>boundary |
| VR 7<br>Brest<br>21.4.48 | 48.00N<br>03.00W<br>12.25 | No<br>search | 20,000<br>to<br>30,000 | 0.35*g*<br>14 ft./sec. | 35,000<br>approx. | Shallow<br>depression | Stable | No detail<br>appears<br>low | Normal | Doubt-<br>ful | —— |
| VR 8<br>N. Spanish<br>Coast<br>22.4.48 | 43.50N<br>05.55W<br>12.40 | No<br>search | 30,000<br>to<br>35,000 | 0.3*g*<br>12 ft./sec. | 30,000<br>approx. | Shallow<br>L.P.<br>trough | Isothermal | No<br>detail<br>appears<br>low | Normal | Doubt-<br>ful | Tropopause |
| VR 27<br>Heligoland<br>6.7.48 | 54.00N<br>07.50E<br>15.20 | About<br>50<br>miles | 32,000<br>to<br>33,500 | 0.2*g*<br>10 ft./sec. | 33,500 | Moderate<br>L.P.<br>trough | Almost<br>isothermal | No detail<br>appears<br>low | Normal | Doubt-<br>ful | Associated with<br>tropopause |
| VR 42<br>Genoa<br>7.9.48 | 44.33N<br>08.08E<br>12.40 | About<br>60<br>miles | 20,000<br>to<br>22,000 | 0.3*g*<br>11 ft./sec. | 38,000<br>not<br>associated | Moderate<br>L.P. trough<br>deepening | Stable<br>marginal | Moder-<br>ate | Normal | Not<br>asso-<br>ciated | —— |
| VR 54<br>Gloucester<br>28.10.48 | 52.00N<br>02.25W<br>14.30 | No<br>search | 23,500<br>to<br>26,000 | 0.2*g*<br>8 ft./sec. | 31,500<br>not<br>associated | Shallow<br>depression | Just<br>stable | Low | Low | Doubt-<br>ful | —— |
| VR 60<br>Stoke-on-<br>Trent<br>8.12.48 | 53.00N<br>02.30W<br>13.00 | About 30<br>miles<br>in one<br>direction | 17,000<br>to<br>28,700 | 0.7*g*<br>26 ft./sec. | Possible<br>double<br>tropopause<br>at 28,700<br>and 33,000 | Jet<br>stream | Stable<br>to very<br>stable | Moder-<br>ate | Modera-<br>ate | Asso-<br>ciated | Jet stream |
| VR 80<br>Cranfield<br>22.4.49 | 52.05N<br>00.20W<br>10.00 | No<br>search | 36,000<br>to<br>? | 0.3*g*<br>15 ft./sec. | 34,500 | Moderate<br>L.P.<br>trough | Iso-<br>thermal | Moder-<br>ate | Moder-<br>ate | Not<br>asso-<br>ciated | Smooth lift (1,500-<br>2,000 ft/min) found<br>from 34,500 ft. to<br>36,000 ft. followed<br>by turbulence |
| VR 81*a*<br>Cranfield<br>25.4.49 | 52.05N<br>00.20W<br>12.00 | No<br>search | 32,000<br>to<br>33,000 | 0.2*g*<br>11 ft./sec. | 33,000 | Deep<br>L.P.<br>trough | Very<br>stable | Moder-<br>ate to<br>low | Low | Asso-<br>ciated | Just below<br>tropopause |
| VR 81*b*<br>Cranfield<br>25.4.49 | 52.05N<br>00.20W<br>12.20 | No<br>search | 22,500<br>to<br>23,500 | 0.2*g*<br>8 ft./sec. | Not asso-<br>ciated | Deep<br>L.P.<br>trough | Very<br>stable | Uncer-<br>tain | Low | Asso-<br>ciated | —— |
| VR 91<br>N. France | 49.32N<br>02.02E | No<br>search | 22,000<br>to | 0.3*g*<br>11 ft./sec. | 30,000<br>steep | Deep<br>L.P. | Stable | Moder-<br>ate | Moder-<br>ate | Doubt-<br>ful | —— |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| VR 81*b*<br>Cranfield<br>25.4.49 | 52.05N<br>00.20W<br>12.20 | No search | 22,500 to 23,500 | 0.2*g*<br>8 ft./sec. | Not associated | Deep L.P. trough | Very stable | Uncertain | Low | Associated | ——— |
| VR 91<br>N. France<br>2.6.49 | 49.32N<br>02.02E<br>12.40 | No search | 22,000 to 25,000 | 0.3*g*<br>11 ft./sec. | 30,000 steep slope | Deep L.P. trough | Stable | Moderate | Moderate | Doubtful | ——— |
| VR 94<br>North Sea<br>10.6.49 | 53.00N<br>02.00E<br>12.20 | 60 miles by 30 miles | 22,000 to 26,000 | 0.6*g*<br>24 ft./sec. | 30,000 | Very shallow L.P. trough | Part stable, part unstable | Uncertain | Low | Doubtful | Turbulence associated with peculiar cirrus formation |
| VR 106<br>Cranfield to Lisbon<br>5.7.49 | On most of route search made at 43.00N 06.30W 13.30 | Brest Peninsular to Portugal (about 500 miles) | 32,000 to 34,000 | 0.2*g*<br>10 ft./sec. | 40,000 falling to 35,000 | Almost featureless | Stable | Low | Low | Not associated | ——— |
| VR 112<br>Skagerrack<br>14.7.49 | 57.00N<br>09.00E<br>12.00 | About 100 miles | Slight turbulence from 24,000 to 35,000 | 0.2*g*<br>7 ft./sec. | About 35,000 | Slack gradient between two depressions | Just stable | Low | Low | Not associated | Ahead of dense, cumulo - nimbus, possibly thermal instability |
| VR 131<br>North Sea<br>16.9.49 | 54.10N<br>04.40E<br>13.00 | 15 miles E.W. Not known N.S. | 29,500 to 33,000 | 0.4*g*<br>20 ft./sec. | 32,500 | Moderate depression | Part isothermal, part just stable | Low | Low | Doubtful | Each side of the tropopause, associated with a band of cirro-stratus |
| VR 135<br>North Wales<br>22.9.49 | 52.35N<br>03.58W<br>10.40 | Uncertain, about 60 miles dia. | 30,000 to 32,000 | 0.2*g*<br>11 ft./sec. | 31,000 | Moderate depression | Stable, part isothermal | Moderate | Moderate | Doubtful | Associated with tropopause |
| VR 138<br>North Spain<br>27.9.49 | 42.33N<br>03.45W<br>12.00 | About 30 miles diameter | 19,000 to 21,000 | 0.4*g*<br>14 ft./sec. | About 38,000 not associated | Shallow depression | Isothermal between almost unstable layers | Low | Moderate | Not associated | Horizontal temperature variation found |
| VR 159<br>N.E. Spain<br>29.11.49 | 41.45N<br>00.20W<br>13.40 | No search | At about 30,000 | 0.2*g*<br>8 ft./sec. | About 30,000 | Shallow depression | Not known | Low | Low | Doubtful | Altimeter was u/s. |
| VR 176<br>Cranfield<br>12.1.50 | 52.15N<br>00.55W<br>15.00 | About 30 miles | 35,000 to 36,000 | 0.3*g*<br>12 ft./sec. | 34,500 | High pressure ridge | Isothermal | Moderate | Low | Not associated | Horizontal temperature variation found |
| VR 179<br>Montreux<br>18.1.50 | 46.30N<br>07.00E<br>13.00 | About 100 miles | 27,500 to 31,000 | 0.4*g*<br>16 ft./sec. | 27,000 | Moderate depression | Almost isothermal | Low | Low | Doubtful | Horizontal temperature variation found |

$\frac{\partial T}{\partial z}$ from aircraft observations; $\frac{\partial V}{\partial z}$ and $\frac{\partial V}{\partial s}$ from synoptic charts.

upper air was smooth, or at least giving $< \pm 0.2g$ accelerations, but that every now and again an area of turbulence was met which yielded accelerations of all magnitudes up to the maximum recorded in that area. Therefore, although expressing the results as "miles to fly to meet a gust of given size" may be convenient, gusts must not be imagined as being spaced out more or less evenly in the upper air, but rather as occurring in isolated clusters.

The special searching technique adopted by the Mosquito was chosen to enhance the prospects of encountering any turbulence which might exist on the route. Subject to certain assumptions it is possible to calculate the relative chances of meeting turbulence when flying a sawtooth flight plan and when flying level at some height between 15,000 and 35,000 ft. For example, if a turbulent layer 2,000 ft. thick and 50 miles long is assumed to exist somewhere on a given route, then on a sawtooth plan the Mosquito would have four chances in ten of finding it, whereas by flying level the chances would fall to one in ten*. With turbulent areas thicker than 2,000 ft. or less than 50 miles long, the relative advantage of the sawtooth flight plan would decrease, and *vice versa*.

*This assumes equal probability of the turbulent layer being anywhere between the limits of altitude—a point which is discussed later.

Table I shows that the sizes of the actual areas varied widely and as it is most unlikely that an actual long range flight by jet-propelled civil aircraft will be conducted at a constant height, there is no advantage in attempting to apply some simple factor to the actual results to take account of the flight technique. It is far better to consider that the Mosquito met turbulence a little more often than would a civil aircraft operating at these heights, but not significantly so.

The results, therefore, have been presented in Figs. 3, 4 and 5 on the basis of miles actually flown by the Mosquito aircraft.

Table II shows that the number of positive gusts of a given size is rather more than the number of negative ones, but there was a slight, although consistent, tendency for one Peravia instrument to be biased in the positive direction. Consequently no attempt has been made in Figs. 3 to 6 to separate up and down gusts, the total number being used, irrespective of sign, especially as results from other sources tend to confirm the rough equality of up and down gusts.

In Fig. 3 the B.E.A. results show that at around 25,000 ft., *on average*, about 8 miles must be flown to meet a 4 ft./sec. gust, about 60 miles to meet 8 ft./sec., about 400 miles to meet 12 ft./sec., and so on. Most results have been obtained between 20,000 and 30,000 ft., and it is probable that, statistically speaking, the results are most reliable

TABLE II

DISTANCE FLOWN AND NUMBER OF GUSTS ENCOUNTERED IN VARIOUS HEIGHT BANDS

| *Height feet* | *Distance statute miles* | *Sign* | *Equivalent gust velocity—ft./sec. E.A.S.* | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 4-8 | 8-12 | 12-16 | 16-20 | 20-24 | 24-28 |
| 15-20,000 | 12,093 | + | 713 | 81 | 7·5 | 3 | — | 0·5 |
| | | − | 415 | 34 | 11 | 0·5 | — | — |
| 20-25,000 | 23,426 | + | 1,271 | 130 | 32·5 | 13 | 4 | 2·5 |
| | | − | 1,089 | 123 | 26 | 4·5 | 2 | — |
| 25-30,000 | 25,907 | + | 1,606 | 159 | 51·5 | 16·3 | 4 | 2·5 |
| | | − | 1,093 | 118 | 22 | 6·5 | 2 | — |
| 30-35,000 | 26,494 | + | 2,457 | 241 | 32 | 3·3 | — | — |
| | | − | 1,480 | 101 | 9 | 2 | — | — |
| > 35,000 | 4,366 | + | 446 | 34 | 3 | — | — | — |
| | | − | 241 | 19 | 2 | — | — | — |
| All heights | 92,286 | + | 6,493 | 645 | 126·5 | 35·6 | 8 | 5·5 |
| | | − | 4,318 | 395 | 70 | 13·5 | 4 | — |

*Note.*—The fractional numbers of gusts result from the fact that the number of gusts actually recorded in a turbulent layer was corrected when the recording distance did not correspond with the horizontal extent of the layer (*see* Equation (2)).

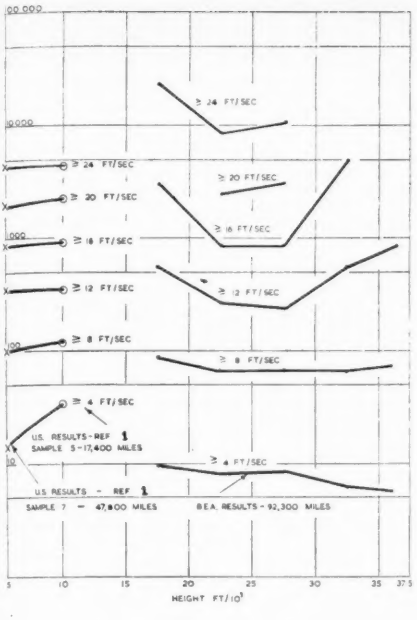


Fig. 3.

Miles to fly to meet a gust of given magnitude or greater, *versus* altitude.

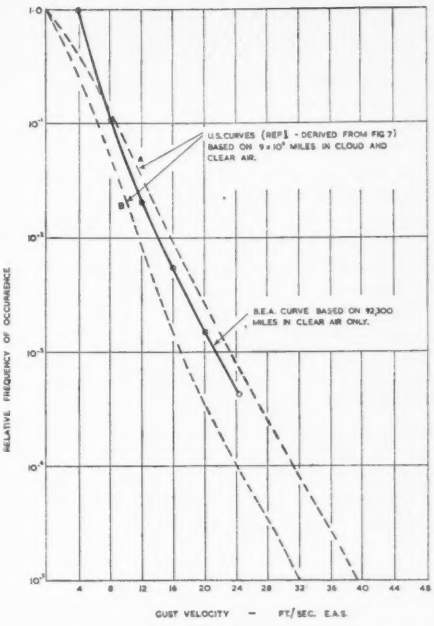
U.S. CURVES (REF 1 - DERIVED FROM FIG 7) BASED ON 9 x 10⁴ MILES IN CLOUD AND CLEAR AIR.
B.E.A. CURVE BASED ON 92,300 MILES IN CLEAR AIR ONLY.
RELATIVE FREQUENCY OF OCCURRENCE
GUST VELOCITY - FT/SEC. E.A.S.

Fig. 4.

Relative frequency of occurrence of gusts of various magnitudes.

between those height limits. The apparent increase in distance to be flown for heights less than 20,000 ft. is possibly due to the smaller number of results available at 15,000 ft. The increase in distance at altitudes above 30,000 ft. when gusts greater than 12 ft./sec. are considered, is also a reflection of the fewer results available. In this instance it is possible that the presence of the tropopause is a factor which makes large gusts less frequent than at the lower altitudes. On the other hand the number of small gusts increase at higher altitudes (*i.e.* the average distance to meet one diminishes). This is probably a genuine effect, as the crews frequently reported slight turbulence when passing through the tropopause. On the whole, and bearing in mind that a sample of 92,300 miles is relatively small, the variation with altitude can hardly be classed as of great significance.

### 5.3. Comparison with other gust data

On Fig. 3 are shown some American results of flights through clear and cloudy conditions at lower and moderate altitudes, extracted from Ref. 1*. The samples chosen (numbers 5 and 7) are the only ones from Ref. 1 which are suitable for presentation in this particular form with the B.E.A. data; the samples comprise some 65,200 miles, which is comparable with the B.E.A. coverage. An interesting comparison is afforded between these results and the purely clear air data at much higher altitude, as given by the Mosquito aircraft. It will be observed that the 4 ft./sec. and 8 ft./sec. gusts are encountered more often at high altitude, whereas the 24 ft./sec. gusts were met more often at the lower altitude. Intermediate gust velocities are apparently met just as often at low as at high altitude.

Another way of comparing the Mosquito and the U.S. data of Ref. 1 is given in Fig. 4, which depicts the relative frequency of occurrence† of gusts of various magnitudes,

*Throughout the report American gust velocities have been made comparable with the corresponding British gust velocities by dividing them by 0.6 approximately.

†Defined as "the ratio of the number of gusts equal to, or greater than, a given gust velocity to the total number of gusts recorded."

irrespective of altitude. In this figure, the Mosquito data have a threshold value of 4 ft./sec., whereas the U.S. data have a much lower threshold value, thus accounting for the different origins*. The U.S. curves "A" and "B" are the broad limits within which fell the results of $9 \times 10^6$ miles of operation, and thus they can be regarded as a good sample of the relative frequency of gusts to be expected over low and moderate altitudes in cloudy and clear air.

It is extremely interesting to see how the B.E.A. curve not only lies between these two limiting curves, but has the same slope at higher gust velocities. This confirms in another way, the findings of the preceding paragraph, *i.e.* that there is little difference between the frequencies of occurrence of gusts of moderate intensities at low altitude and at high altitude in clear air. It also suggests that one can extrapolate with fair confidence on this diagram up to gust velocities of about 36 ft./sec.

### 5.4. Extrapolation to higher gust velocities

In dealing with this question of extrapolation, it is considered both justifiable and statistically more satisfactory to neglect the slight variation with altitude and present all the B.E.A. data as a plot of miles to fly to meet a gust of given intensity *versus* gust velocity. This has been done in Fig. 5. Also shown are some results of *V-g* recorder analyses conducted by the R.A.E.[2, 3] on Constellation and Liberator operations, together with Samples 4, 5, 6, 7 from Ref. 1.

It is notable that all results agree reasonably well at low and moderate gust velocities, *i.e.* up to about 16 ft./sec. Beyond that point the B.E.A. results diverge from the others, although the latter are in reasonably good agreement with each other up to the highest gust velocities. This divergence of the purely clear air data from the remainder may well be a genuine effect, for which some support can be adduced from Fig. 6, which shows a similar difference.

In a private communication, Starkey of the R.A.E. suggested that a law of the "negative binomial" type might fit the B.E.A. results and it is clear from Fig. 5 that it does so very well, but the extrapolation beyond the largest observed vertical gust velocity of 26 ft./sec. is seen to lie somewhat above the *V-g* results. No special physical significance can be attached to this extrapolated curve, although it is probable that the clear air gust distribution will tend to lie above the *V-g* results. The negative binomial extrapolation may be a little optimistic, but it is a reasonable compromise to offer at this stage, at least for gust velocities up to about 36 ft./sec. The R.A.E. have suggested [4, 5] from their own results on Spitfire aircraft that the distribution of clear air gust magnitudes follows a normal error law, but any attempt to fit such a curve to the B.E.A. results gives much too small a chance of meeting moderate or severe gusts.

Some confirmation of the suggestion that even the negative binomial distribution may err on the optimistic side, is forthcoming from the widely reported occurrence when the Comet on its early development trials encountered severe turbulence at high altitude[6]. The actual equivalent gust velocity at the c.g. of the Comet was not recorded in this instance, but it was probably around 35 ft./sec. Even allowing for the probability that the mileage flown at the time of the occurrence (about $6 \times 10^4$ miles above 15,000 ft.) has possibly trebled since then and no further turbulence of this order has been reported, yet the corresponding point lies between the negative binomial extrapolation and the *V-g* data. The broad conclusion is that the Comet episode cannot be regarded as a freak.

To put the matter into perspective it is of interest to consider what would be involved in operating a fleet of 20 aircraft, broadly of the Comet type. At an annual utilisation of 3,000 hours the total distance flown in a year might be about $27 \times 10^6$ miles. On the negative binomial extrapolation, a 36 ft./sec. gust would be met, therefore, on average, once a fortnight, and a 50 ft./sec. gust once in four years. These gust velocities correspond approximately to acceleration increments of $1.5g$ and $2g$ respectively at the assumed cruising conditions.

It is quite clear that much more data are needed to present a reliable picture to the aircraft designer and to the airline operator. The Comet episode underlines this need.

*The U.S. data, as given in the original report, have been corrected to the British gust standards. In addition, the relative frequencies have been doubled in order to present a direct comparison with the B.E.A. results, which do not discriminate between positive and negative gusts.

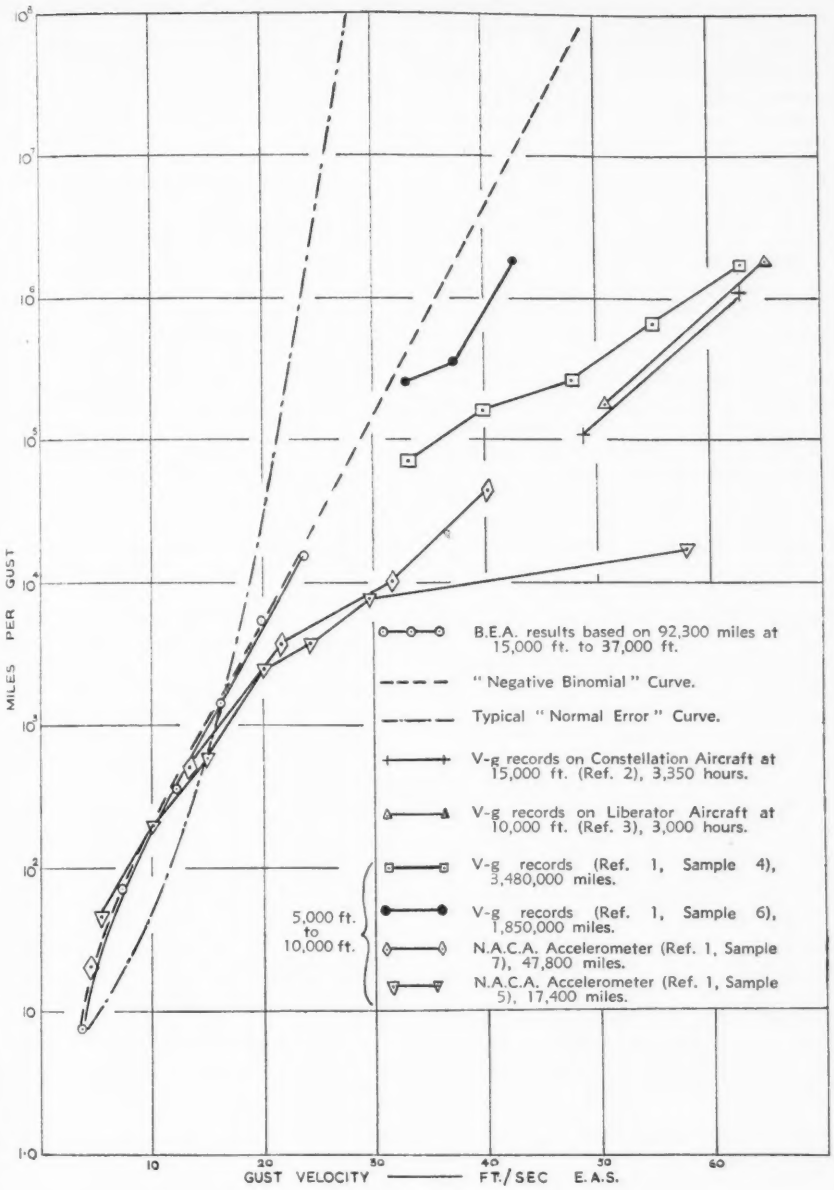
MILES PER GUST
GUST VELOCITY —— FT./SEC E.A.S.
B.E.A. results based on 92,300 miles at 15,000 ft. to 37,000 ft.
" Negative Binomial " Curve.
Typical " Normal Error " Curve.
V-g records on Constellation Aircraft at 15,000 ft. (Ref. 2), 3,350 hours.
V-g records on Liberator Aircraft at 10,000 ft. (Ref. 3), 3,000 hours.
5,000 ft. to 10,000 ft.
V-g records (Ref. 1, Sample 4), 3,480,000 miles.
V-g records (Ref. 1, Sample 6), 1,850,000 miles.
N.A.C.A. Accelerometer (Ref. 1, Sample 7), 47,800 miles.
N.A.C.A. Accelerometer (Ref. 1, Sample 5), 17,400 miles.

Fig. 5.
Miles to fly to meet a gust of given magnitude or greater *versus* gust.

### 5.5. Comparison with conditions in thunderstorms

In the discussion so far the frequency has been considered with which gusts are met when flying through the atmosphere as a whole, *i.e.* through both rough and smooth air. It is interesting to examine the results from clear, turbulent air only. The weakness of this examination is that accelerometer recordings are available only for some 500 miles of turbulent air—a very small sample indeed. The results are portrayed in Fig. 6 and, for comparison, data from the U.S. Thunderstorm Project[7] and some British results[17] from a survey conducted jointly by the Meteorological Office and the R.A.E., using Spitfire aircraft, are also shown. It is immediately obvious that in thunderstorms the proportion of high to low gust velocities is greater than in clear turbulent air, also that the gusts are rather closer together. It follows also, that the probability of meeting very severe gusts is much greater in thunderstorms than in clear air.

It is of great interest to note that the Thunderstorm Project has stated[7] ". . . if the largest gust in a group of several contiguous gusts exceeds about 15 ft./sec.* and at the same time the gust frequency is greater than 8 per 3,000 feet of traverse, the Project air crews reported the turbulence as "heavy." When the region under consideration is expanded to the length of one complete pass through a thunderstorm, heavy turbulence was reported for the traverse as a whole whenever the mean maximum effective gust velocity per 3,000 feet of traverse exceeded 8 ft./sec.† and the frequency exceeded 4 per 3,000 feet of traverse." This yardstick has been applied to one of the B.E.A. traverses in turbulent air (VR 94) and the essential results are shown tabulated. The recording from this voyage was broken down into successive lengths of 3,000 ft. corresponding to about 5 or 6 seconds running time.

| No. of 3,000 ft. length | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| $U_{max}$, ft./sec. (U.K.) | 8 | 12 | 20 | 24 | 12 | 16 | 12 | 20 | 4 | 4 |
| No. of peaks >4 ft./sec. in 3,000 ft. length | 5 | 10 | 9 | 11 | 6 | 8 | 4 | 7 | 1 | 2 |

*25 ft./sec. on Mosquito by U.K. standards.

†13.3 ft./sec. on Mosquito by U.K. standards.

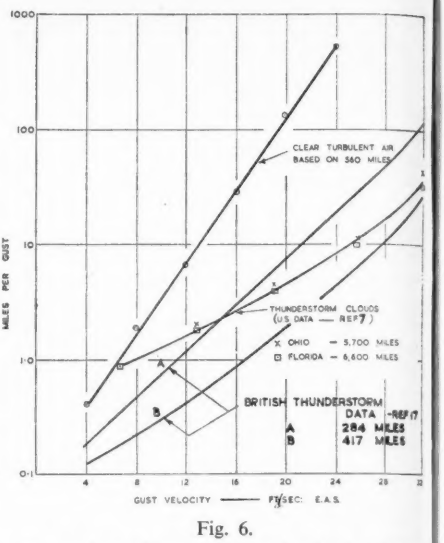


Fig. 6.

Comparison of mean gust spacing in clear turbulent air and in thunderstorm clouds.

It will be seen from length numbers 3 to 8 inclusive that the U.S. standard for heavy turbulence has been generally exceeded. The sample given is probably the longest stretch of severe roughness which has been recorded and analysed, but others just as severe (by inspection) have been noted over shorter lengths.

Following up the U.S. definition of heavy turbulence, which depends upon the length of the "pass," it is probable that a lower standard of definition of "heavy" turbulence would have been adopted had the distance in turbulent air been of the order of 50 or 100 miles—which is representative of clear air turbulence—instead of the representative thunderstorm dimension, say around 10 miles.

### 5.6. Effect on fatigue of aircraft structure

No attempt has been made to analyse the results in terms of fatigue of the aircraft structure. It is preferred to leave this aspect to the specialists in such matters, especially as there is considerable controversy about the best method of combining the fatigue effects due to the different frequencies and amplitudes of a representative loading spectrum.

## 6. METEOROLOGICAL ASPECTS

### 6.1. General considerations

From the civil operator's point of view the lack of warning of this type of turbulence makes the main aim of the meteorological attack on this problem the development of a reliable basis for forecasting its occurrence. This implies that an explanation must be found as to why turbulence exists at all in the upper atmosphere and this in turn must be linked with the meteorological situation(s) which can give rise to the conditions essential for the maintenance of turbulence. If there were a large number of fully reported cases of clear air turbulence, it might be possible to deduce the principal cause, or causes, by statistical methods alone. This line of attack obviously cannot yield a reliable answer when the present investigation* yielded only some twenty cases of clear air turbulence (as defined in Section 3) and 162 voyages where no such turbulence was met —especially when an extremely complex subject like meteorology is involved.

The other method of tackling the problem is to examine the immediate physical causes of atmospheric turbulence and then attempt to obtain experimental confirmation by actual observation in turbulent regions (with a cross-check in non-turbulent regions). These physical causes must then be related to the meteorological conditions which generate them, thus providing a basis for forecasting. In this paper is given an outline of the various possibilities and the reasons which led to the conclusion that wind shear in the vertical is the most likely cause of clear air turbulence; in addition, mention is made of other factors which have been put forward and which have had to be rejected as unlikely, except possibly in special cases. Lack of space makes it difficult to go into this most fascinating side of the investigations in the full detail which it deserves, but a full account has been given in a report[8] to the Ministry of Supply.

### 6.2. Sources of turbulent energy

Since turbulence involves the dissipation of energy, energy must be supplied at a rate sufficient at least to counterbalance this dissipation. There are three main sources of turbulent energy: thermal instability, wave motion, and wind gradients. The possibility that thermal instability was a general cause can be disregarded, as in the great majority of cases a most noticeable feature was that the temperature lapse rate was markedly stable (*see* Table I and Fig. 9).

Atmospheric waves are known to exist in association with mountains[9], but the wavelength of the resulting disturbance would merely result in a change in height of the aircraft, not in the encountering of turbulent motion. Cold fronts also have been reported[10] to give rise to atmospheric waves. There is a possibility that under certain conditions atmospheric waves may "break"—as a sea wave does—and thus degenerate into turbulent motion; so far as I am aware there is no mathematical case covering such a breakdown in wave motion. It is interesting to observe, however, that on one occasion a B.E.A. Mosquito experienced smooth lift of about 1,500 to 2,000 ft./min. between 35,000 ft. and 37,000 ft., which finally petered out into rather sluggish turbulence in the stratosphere.

The third source of energy may now be considered in more detail, as it is believed that this is the most probable cause of clear air turbulence.

If, in the presence of a wind gradient in the vertical (*i.e.* $\partial V/\partial z$) no turbulence is present, then the purely viscous forces in the atmosphere are small. In practice, some turbulence will exist and the eddies will diffuse in the vertical and horizontal, tending to break down the wind gradient. The eddies can be regarded in fact as a means of dissipating energy.

The original theoretical approach linking turbulence with vertical wind gradient was developed by Richardson[11], whose reasoning was as follows:—

If in a vertical wind gradient, some initial turbulence and hence eddy diffusion does exist, then

$$\text{Rate of energy supply} \propto (\partial V/\partial z)^2.$$

But diffusion in the vertical does work against gravity, the amount of work being proportional to the thermal stability—*i.e.* the amount by which the actual vertical temperature lapse rate differs from the lapse rate for instability. In fact

$$\text{Energy dissipated} \propto \left(\frac{\partial T}{\partial z} + \Gamma\right).$$

*Investigations by the R.A.E.[4, 5] and Bannon[13] reported additional cases of turbulence, but the technique adopted and the information obtained from these sources were such that no satisfactory correlations with prevailing meteorological conditions could be established.

Richardson states that if the rate of supply of energy exceeds the rate of dissipation, existing turbulence would tend to increase. The relation can be written

$$\left(\frac{\partial V}{\partial z}\right)^2 > \frac{g}{T}\left(\frac{\partial T}{\partial z} + \Gamma\right) \quad . \qquad (3)$$

for turbulence to increase.

Various refinements to this relationship have been put forward but without affecting the basic idea, and for the purpose of this paper, it is sufficient to note that the local wind gradient in the vertical is obviously a most important parameter in deciding whether or not turbulence is likely to exist.

### 6.3. Vertical wind gradient

Realising the importance of the local wind gradient in the vertical, the B.E.A. unit gave a great deal of thought to its accurate determination. Quite apart from the fact that the normal radio-sonde wind information available gives observations of the wind at intervals of several thousand feet (at high altitude at least), the fact that turbulence might be encountered anywhere over Europe and far beyond the reach of existing radio-sonde stations, made us bend our attention to means whereby it could be determined from the aircraft at the time and place required.

Direct methods of attack, such as by use of a pitot trailed two or three hundred feet below the aircraft, or by laying vertical smoke trails and observing the relative shift, were considered in detail. While ultimately practical, they had to be rejected as they required development beyond the resources of the unit.

An indirect approach was then proposed by my colleague, D. M. Davies, who suggested that the relation between the vertical wind gradient and the horizontal temperature gradient as expressed in the familiar thermal wind equation might be tried. This equation can be expressed[19] in the form

$$\frac{\partial V}{\partial z} = \frac{g}{T}\,\frac{\partial T}{\partial s}\,\frac{1}{2\Omega \sin\phi} \quad . \qquad (4)$$

Hence at a given latitude $\phi$, the wind gradient $\partial V/\partial z$ is a direct function of the absolute temperature $T$, and the temperature gradient in the horizontal $\partial T/\partial s$, both easily determined factors. Hence, if observations of temperatures, taken at frequent intervals over a distance of at least 50 miles, showed a marked temperature gradient, the presence of a marked vertical wind gradient would be deduced.

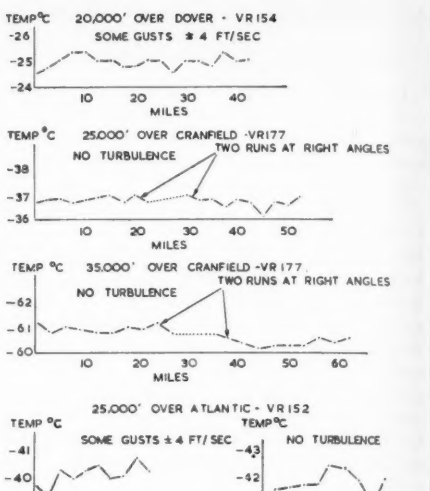


Fig. 7.

Horizontal temperature traverses in smooth air (▷ 4 ft./sec. gusts).

In order to verify that the foregoing relationship was valid, or at least roughly so, experimental observations of the horizontal temperature gradient in both smooth and turbulent conditions were clearly needed. A number of level runs were made in smooth air. Thermometer readings were taken every 30 seconds (roughly every 2½ miles) while pressure height and air speed were held constant. The results of these runs are shown in Fig. 7. Variations do take place, but they are fluctuations of $\pm 0.5°C.$ to $\pm 1.0°C.$ about a mean; there is little change of mean temperature. This confirms observations of the Meteorological Research Flight[12].

Before the closing down of the unit it was found possible to make three runs through turbulent regions and the results are shown in Fig. 8. Ideally, two runs at right angles should be made, but for operational reasons, this was not possible in all cases. The runs, therefore, were made at right angles to the forecast or navigation wind, which would be

expected to give the maximum rate of change of temperature. On all occasions a marked variation of temperature was found, as is clearly shown.

When considering the temperature gradients shown in Fig. 8 in the light of the thermal wind equation, the assumptions on which the equation is based must be borne in mind, *i.e.* steady atmospheric conditions. In actual fact the conditions are seldom steady and hence the equation does not hold strictly. Nevertheless, it is believed that under conditions where the atmospheric pressure is changing, the actual wind velocity lags only slightly behind the theoretical wind corresponding to these conditions. To generate an increment in wind of about 30 knots the pressure gradient must extend for some 70 to 80 miles; similarly, temperature variations which do not extend for more than about five miles or so have little significance. Hence, it is believed that as a first approximation and to give a guide as to the probable order of the vertical wind shear, the thermal wind equation can be applied with fair confidence.

Turning now to Fig. 7, it can be said with certainty that, so far as VR 177 was concerned, the Daily Weather Reports showed that the vertical wind gradients were small; in the other two cases equally strong evidence is not available, but it appears from the charts that the gradients were small.

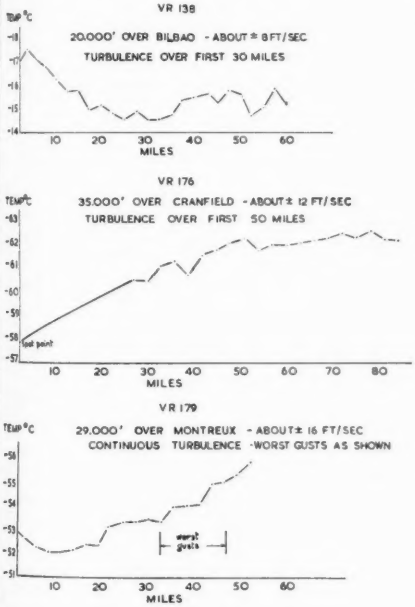
VR 138
20,000' OVER BILBAO - ABOUT ± 8 FT/SEC
TURBULENCE OVER FIRST 30 MILES
MILES
VR 176
35,000' OVER CRANFIELD - ABOUT ± 12 FT/SEC
TURBULENCE OVER FIRST 50 MILES
MILES
VR 179
29,000' OVER MONTREUX - ABOUT ± 16 FT/SEC
CONTINUOUS TURBULENCE - WORST GUSTS AS SHOWN
MILES

Fig. 8.
Horizontal temperature traverses in turbulent air.

For the rough air traverses of Fig. 8, a straightforward application of the thermal wind equation gives a vertical wind gradient of about 15 knots per 1,000 feet. Now a critical vertical wind gradient can also be derived from Richardson's criterion (equation (3), Section 6.2) by making use of the observed temperature lapse rate in the vertical. In all three cases the thermal stability was most marked, being about 2 or 3°C. per 1,000 ft., which, when coupled with the mean ambient temperatures in each instance, gives a minimum vertical wind gradient to sustain turbulence of about 10 to 12 knots per 1,000 ft.

Hence in the turbulent regions it has been shown that the observed horizontal gradient of temperature implied the existence of a high vertical wind gradient. Also that this vertical wind gradient, when coupled with the observed temperature lapse rate satisfies the Richardson criterion for turbulence, within reasonable limits of experimental accuracy. Since only three cases were investigated, the result must be accepted with caution, but it is at least interesting and suggestive.

In one case (VR 176) a radio-sonde ascent was available corresponding closely in time and position to the turbulent area. The radio-sonde measurements showed a vertical wind gradient of only 4 to 5 knots per 1,000 ft. This is not necessarily inconsistent, since the radio sonde at 35,000 ft. would give a mean wind over a height range of 3,000 to 4,000 ft. However it does illustrate the inadequacy of radio-sonde data for an analysis of this sort.

### 6.4. Other meteorological factors

It will be clear from the foregoing that vertical gradient is felt to be the principal cause of clear air turbulence and that the Richardson criterion for turbulence is applicable.

An alternative approach to the problem is to make a detailed examination of the weather and other relevant conditions when voyages have been made and especially on those occasions when turbulence was found, using published meteorological data. The drawback to such a method of examination

is the relative scarcity of the available results. The Meteorological Office is keenly interested in this problem and the B.E.A. results have been sent there for analysis in conjunction with reports from other sources. A report[13] has been issued by the Meteorological Office which included some of the early B.E.A. data, but the result is rather disappointing in that, while certain trends become evident, the analysis does not yield clear cut correlations which can be used for forecasting purposes. It is possible that the critical parameters are still completely unknown, but a more likely explanation perhaps is that the meteorological data are insufficiently detailed and accurate for this purpose. It is conceivable that localised regions can occur where conditions are significantly different from the surroundings. Such localised regions may be small enough to be missed by the radiosonde network. In the United Kingdom stations are about 150 miles apart and ascents are made every six hours. Over much of Europe the intervals of time and distance are much greater.

In a paper such as this it is not practicable or necessary to give the full meteorological details pertaining to each flight. Certain basic information is given for all the flights on which turbulence was found (Table I), a few specimen tephigrams (Fig. 9), and a few examples of synoptic situations of especial interest (Figs. 10, 11, 12). A number of meteorological factors which might have a bearing on the occurrence of turbulence, or which might be correlated with the presence of turbulence, have been examined closely, and the essence of the findings is discussed.

### 6.4.1. *Jet streams*

One meteorological condition which, by definition, is bound to contain regions of high wind shear, is a jet stream, an example of which is shown on the 300 mb, chart on Fig. 10. A jet stream is generally taken as a narrow belt of high wind (100 knots or greater) embedded in an air stream of markedly lower speed, while a vertical cross-section through it has the character illustrated in Fig. 13. It is not necessary to go into a discussion of this phenomenon at any great length as Durst and Davis[14] have already adequately covered the subject in their paper to the Institute of Navigation. Suffice it to say that the highest winds are concentrated in a "jet" and high wind gradients occur at the boundary between warm and cold air. The jet stream in fact is associated with high horizontal temperature gradients (frontal conditions in the upper air) which lead to high wind gradients and hence, to high winds when the gradients extend over an appreciable height range.

From the earlier arguments in this paper it would be expected that clear air turbulence would be found associated with jet streams, and this is sometimes the case*. Severe turbulence was twice found in a jet stream (VR 4 and VR 60). On the other hand, on more than twenty other occasions the search aircraft flew across the axis of, or near, a jet stream without incident. On VR 60, the aircraft flew out from base in smooth air and returned on a reciprocal course about 30 minutes later to find severe turbulence, although crossing the jet stream boundary on both the outward and return trips (*see* Fig. 10). Furthermore, when making a search of the turbulent area, turbulence was found to be patchy and intermittent. This illustrates the localised nature of the phenomenon. A possible explanation is that even in jet streams, where high wind gradients are expected to occur, conditions become critical only in regions of limited extent.

From experiences reported by other aircraft, a notable example being the Comet incident already referred to[8], one is tempted to suggest that the most severe cases occur in jet streams, although the evidence is still very limited.

### 6.4.2. *Tropopause*

Of the twenty cases given in Table I, ten were within 2,000 ft. of tropopause, some above, some below. This is rather puzzling since the tropopause is normally assumed to be a region of zero vertical wind gradient—the boundary in fact between increasing winds in the troposphere and decreasing winds in the stratosphere where the thermal wind effect is usually reversed.

Two of the horizontal temperature runs shown in Fig. 8 were just above the tropopause, suggesting that under certain conditions high wind gradients can occur near the tropopause. (An example of this, based on the thermal wind effect, is when the

*From about March 1949 flights were planned to cross jet streams whenever the Central Forecasting Establishment, Dunstable, notified the unit that a jet stream was forecast within the operational range of the aircraft.

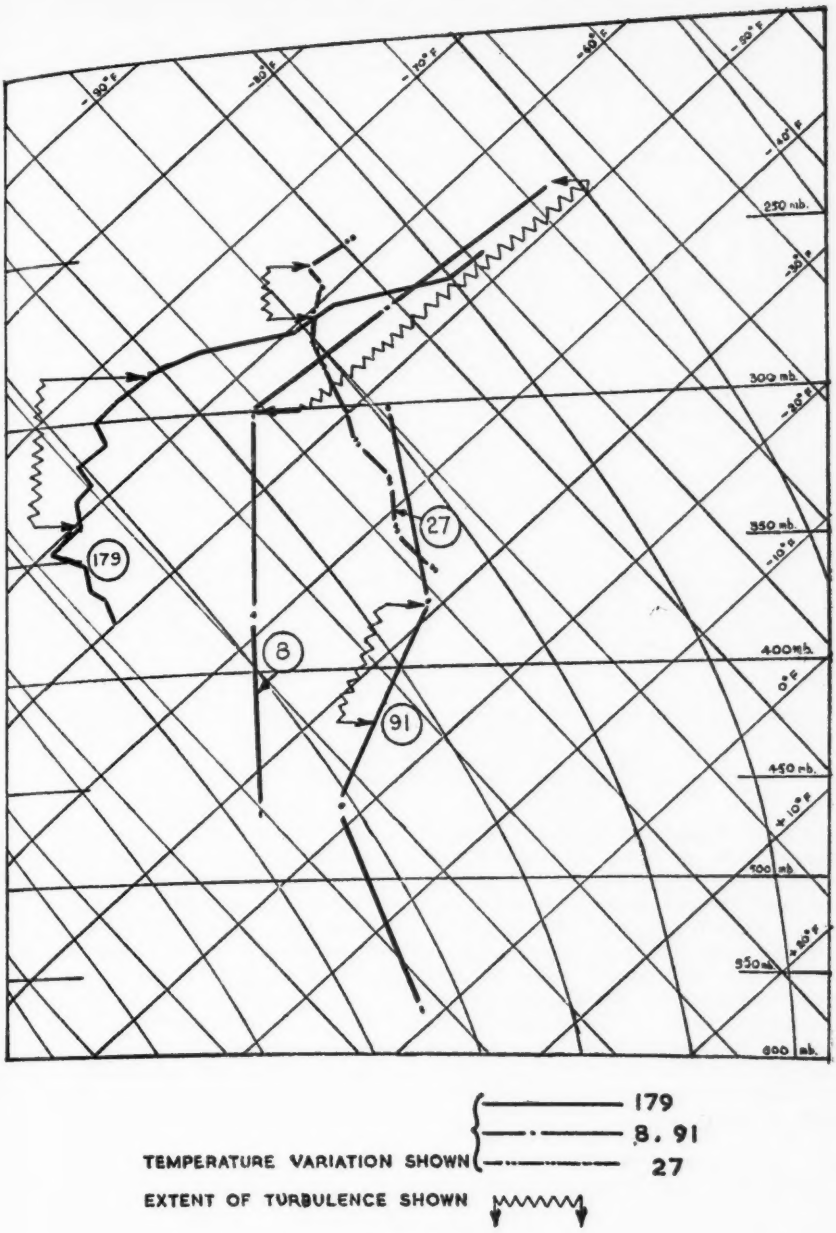


Fig. 9.
Tephigrams of positive voyages.

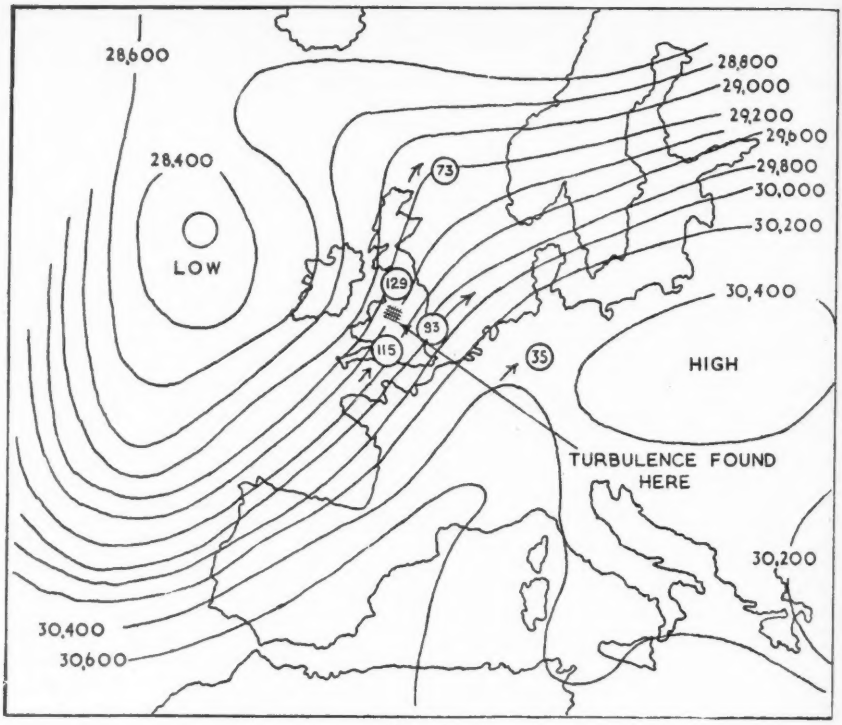


Fig. 10.
Example of jet stream as shown on 300 mb. chart (from VR 60).
(Figures give the height of the 300 mb. surface.)

tropopause is sloping and the stratosphere is isothermal in the vertical.) The slope of the tropopause as shown by the upper air section of the Daily Weather Report is normally of the order of 1,000 to 2,000 ft. per 100 miles. Above certain depressions the slope is sometimes shown to be as much as 4,000 to 6,000 ft. per 100 miles and this might generate wind gradients of the order of 10 knots/1,000 ft. in the substratosphere. Of the ten cases mentioned, four were near a region of very steep tropopause slope. Fig. 11 shows an example of this. Table I shows that most cases were associated with low pressure regions or troughs although this does not necessarily result in a steep tropopause slope.

### 6.4.3. *Marked high or low pressure regions in the upper air*

If a region of marked low or high pressure exists in the upper air, the resulting circulation may bring air masses at different temperatures into proximity. Fig. 12 shows an example of an upper air depression. Table I shows that all but three of the cases considered were connected with upper air depressions or troughs, although sometimes the troughs were very shallow and might well be considered insignificant.

### 6.4.4. *Thermal instability*

Most of the temperature lapse rates (*see* Table I and Fig. 9) for all twenty cases of turbulence were stable, or very stable, tending to the isothermal. Some cases, however, showed marginal stability. Thus on VR 131 bumps were found associated with cirrostratus cloud—cloud which is normally quite innocuous. Very curious cloud effects were noted on VR 94. To quote the pilot, "The most remarkable feature of the cloud was a series of corrugations like teeth isolated in clear air. These teeth were 50 to 100 ft. high and appeared singly or in groups of two

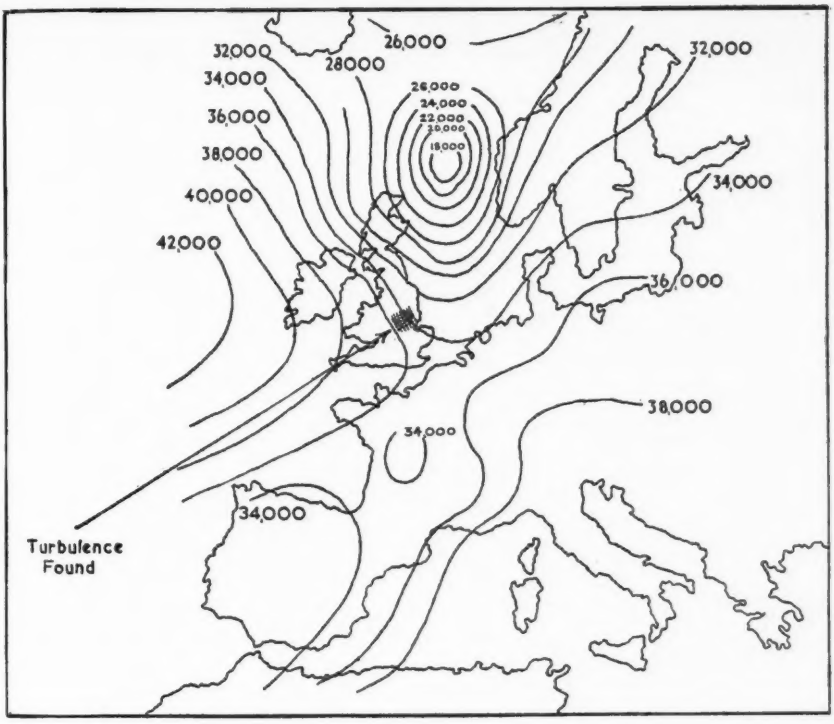


Fig. 11.
Example of a steeply sloping tropopause (from VR 80).

or three. Above one or two some wispy cirrus appeared to be suspended, giving the effect of a miniature mountain with its peak immersed in wispy cloud. Marked turbulence was experienced on flying through some of these teeth . . . which appeared to be 100 to 200 ft. apart." On VR 131 the lapse rate was just unstable through the cirro-stratus and isothermal above and below. On VR 94 the lapse rate was generally stable with regions of instability over limited height bands. It may be noted that when a large horizontal variation of temperature occurs, the warm air would normally over-ride the cold air—giving a stable temperature lapse rate. For this reason it is not easy to link up high wind gradient with unstable temperature lapse rate.

6.4.5. *Wind speed*

An examination has been made of the occurrence of turbulence in relation to wind speed, as distinct from wind gradient, but without any consistent result. Turbulence has occurred at wind speeds from five knots to 150 knots and 90 per cent. of cases occurred below 75 knots. Having regard to the frequency with which high winds occur, the turbulence between 15,000 ft. and 25,000 ft. did show a tendency to become *relatively* more frequent at high wind speeds. There was no such tendency between 25,000 ft. and 35,000 ft. As a forecasting aid, therefore, wind speed would be of little value.

6.4.6. *Polar front*

It would be expected that the polar front would be associated with marked temperature contrasts. As shown in Table I on a number of occasions the polar front had become diffused and could not be identified with certainty. As a result no conclusions can be drawn on this point.

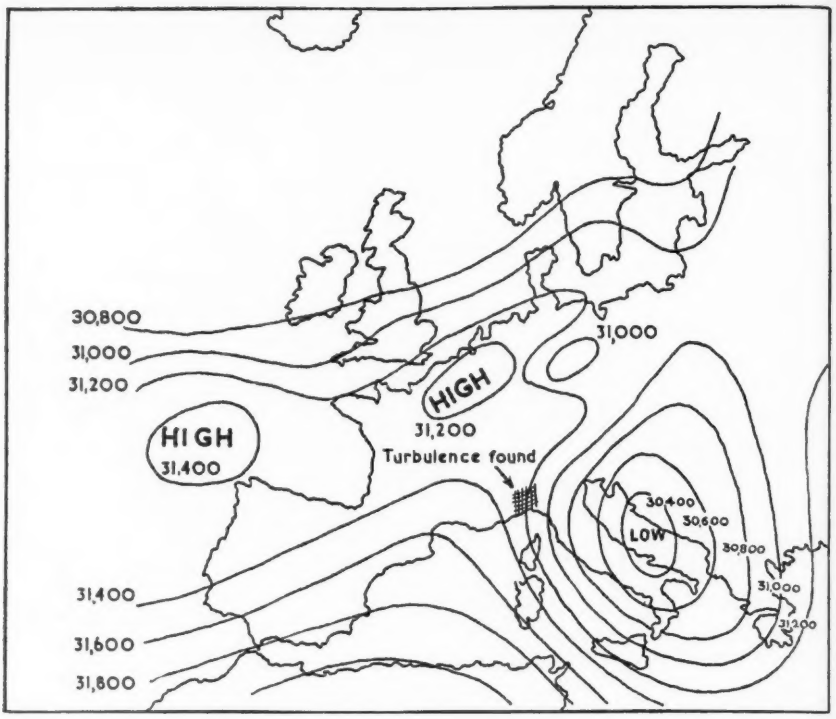


Fig. 12.
Example of upper air depression shown at 300 mb. surface (from VR 42).

6.4.7. *High ground*

It appears unlikely that the effect of high ground would extend to high altitude, except through some form of wave motion. As discussed in Section 6.2 the association of turbulence with wave motion remains speculative. Two cases of turbulence, VR 42 and VR 179, did occur near the Alps. The first case was associated with a marked low pressure region (*see* Fig. 12) and the second with a high horizontal temperature variation. The only case where apparent wave motion made itself evident was in fact VR 80. This occurred at 35,000 ft. over Cranfield and there is no definite evidence relating it to high ground. The fact that, except on this one occasion, wave disturbances were not found does suggest that high ground is not important, except perhaps in a minority of cases.

## 7. DATA FROM OTHER OPERATORS

### 7.1. United air lines (U.S.A.)

United Air Lines, operating DC-6 aircraft between 15,000 ft. and 25,000 ft. in the U.S.A. have cited several cases of clear air turbulence in an unpublished report by Harrison[15]. They have made their own meteorological analysis and report that in every case the turbulence was associated with a jet stream or a "cold low" (a more or less vertical column of air at appreciably lower temperature than its surroundings, associated with a low pressure region at the surface and in the upper air). They further state that the occasions were characterised by a sudden and decided change in both temperature and wind speed in the horizontal. It is of interest to note that these views are generally similar to those already put forward in this paper, although United Air Lines suggest that the

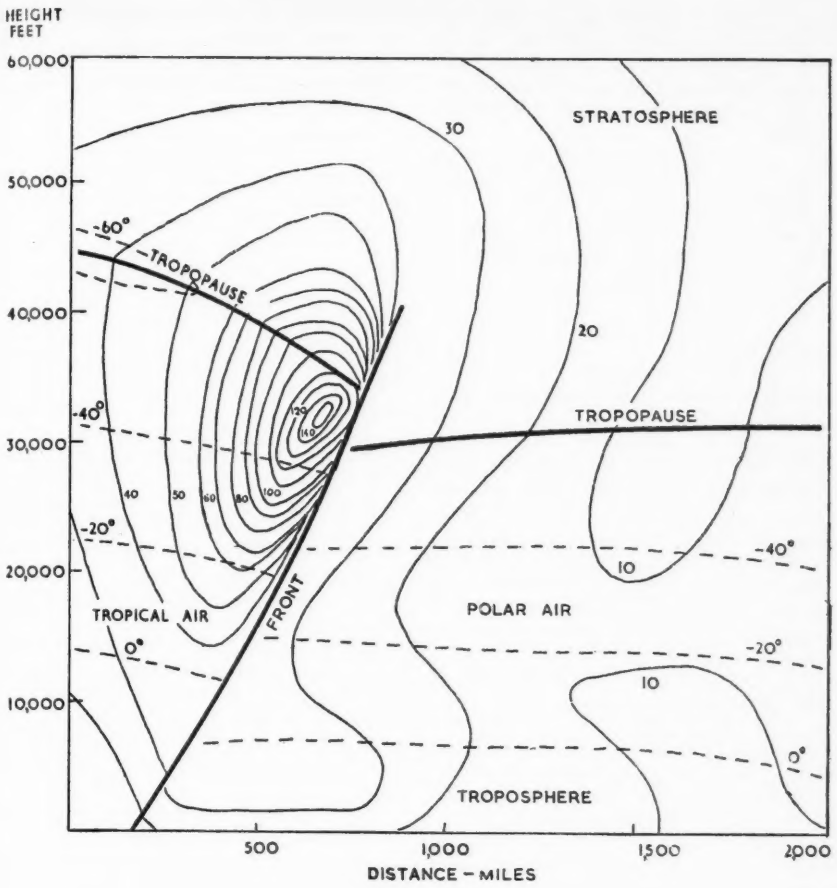


Fig. 13.

Lines of constant wind speed in m.p.h. shown ———— 60

Lines of constant temperature in °C shown — — — — −20

Vertical cross section through representative jet stream.

wind shear in the horizontal is a significant factor*.

### 7.2. B.O.A.C. and the de Havilland Aircraft Co. Ltd.

An arrangement whereby details have been sent to B.E.A. of any clear air turbulence encountered by either B.O.A.C. aircraft or by the de Havilland Aircraft Company's aircraft, has been in existence for some little time. So far, upwards of thirty cases have been reported, but these do not constitute such a mass of evidence as was obtained from the Mosquito investigations, mainly because they are bare reports of what was encountered without any attempt to gather specialised information.

As might be expected, the de Havilland results are generally grouped around Eastern England. B.O.A.C.'s results show a marked grouping at a position about 55° N., 40° W., *i.e.* some hundreds of miles east of

*Bannon[13] has attempted to correlate turbulence with vertical or horizontal wind gradient using normal meteorological sources of information for details of the wind gradients, but with disappointing results.

Newfoundland. Investigation into the meteorological condition prevailing at the time of the incidents is still in progress and it would be premature to generalise at this stage, but a formal report will be prepared in due course.

As a matter of interest a specimen copy of a completed report form from the captain of a B.O.A.C. Stratocruiser is given as Fig. 14. This incident, classed as perceptible to moderate, shows an air temperature rise of 11°C. in about 140 miles.

## 8. DISCUSSION

There is no doubt that further work needs to be done on clear air turbulence from the point of view of forecasting. The results presented in this paper suffer from the basic defect that they are few in number and, for this reason, no conclusion can be regarded as final. Bearing this limitation in mind, the results presented do suggest that the Richardson criterion, with vertical wind gradient as the major parameter, may well give a method of determining conditions which would be expected to generate turbulence. Even if this is in fact the case, the possibility of actually forecasting turbulence is not good. There is reason to suppose that if a very detailed mesh of high altitude reports were available, an accurate forecast could be made. At the present time, however, this cannot be done. Illustrating this, it is pointed out in Section 6.3 that turbulence can occur in limited regions of certain jet streams, but it is not yet possible to predict the position of the jet stream itself with accuracy, let alone to pick out those regions of a jet stream which may generate turbulence. Again, while turbulence is often found near the tropopause, apart from a suggestion that tropopause slope is important (connected in turn with an upper air depression), no formal rules can be laid down for the forecaster. These are problems which no doubt could be solved, but at present they remain problems. At least, it can be said that analysis of meteorological data leads to findings not inconsistent with the idea that wind gradient in the vertical (or horizontal temperature gradient) is the basic cause of most cases of clear air turbulence. Until further information becomes available, this is probably the best basis on which to work. While an accurate forecast of turbulence cannot be made as yet, it is at least possible to pick out, in a very general way, regions where it is most likely to occur.

It is probable that eddies in the atmosphere may range in size from about one foot to several hundreds of feet, until they merge into the general large scale movements of the atmosphere. Within this very wide band are those eddies or gusts which give rise to "bumps" felt by aircraft and, as has already been suggested by Bannon[13], such eddies probably have a linear dimension lying roughly in the range 50 to 500 ft. Eddies smaller than 50 ft. will be felt by a fast aircraft, not so much as a succession of "bumps," but more as an irregular vibration. On encountering eddies much larger than 500 ft., the aircraft attitude will tend to adjust itself to the change in direction of air flow, *i.e.* it will "ride" eddies of this size. These remarks apply to present sizes of aircraft. Much larger and faster aircraft will be sensitive to somewhat larger eddies than the normal present-day aircraft. The data given in the paper, however, will be applicable to aircraft of orthodox design at present envisaged.

Therefore, it can be said that an aircraft employed on gust investigation "filters" the spectrum of atmospheric turbulence and reacts only to eddies within certain limiting sizes. From the purely aeronautical aspect this is no handicap, but obviously other techniques would need to be employed were a more general investigation of atmospheric turbulence to be undertaken.

Little comment has been made on the structural implications of clear air turbulence, but it is felt that this aspect cannot be completely disregarded. The evidence of Fig. 5, coupled with the Comet incident, shows that large gusts may be expected in clear air, although at high altitude the frequency of occurrence is likely to be very much less than at lower altitudes where flights may pass through cumulo-nimbus cloud. Because they are met with little or no warning, clear air gusts will tend to be associated with the normal cruising speed of the aircraft, irrespective of the magnitude of the gusts. On the other hand, the basic gust envelope of the British Civil Airworthiness Requirements associates the largest gust velocity with a speed less than the design cruising speed. The implications of this difference on the design requirements for high flying aircraft should be examined.

Aircraft: Stratocruiser

*Captain*: CRAIG *Navigating Officer*: DONNELLY *Flight No.* 508/053 *Date* 18.4.50

*Sector:* from NEW YORK to PRESTWICK *Locality of Incident:* 48.50 N lat. 42.00 W long.

| | OBSERVATIONS | ONSET OF TURBULENCE | CESSATION OF TURBULENCE |
|---|---|---|---|
| *General* | Time | 21.10 G.M.T. | 21.35 G.M.T. |
| | Pressure Altitude | 25,000 ft. | 25,000 ft. |
| | A.S.I. | 170 kts. | 170 kts. |
| | Aircraft heading | 118°M degrees | 118 degrees |
| *Incident Details* | Magnitude of turbulence: average during incident (2) | occasionally (Perceptible) (x) (Moderate) (x) (Severe) ( ) | |
| *Met. Data* | Distance to nearest cloud (approx.) | miles | miles |
| | Type of cloud (if within 10 miles) | | |
| | Amount of cloud | 10 tenths | 10 tenths |
| | Altitude of tops | 18,000 ft. | 18,000 ft. |
| | Altitude of base | 26,000 ft. | 26,000 ft. |
| | O.A.T. | −38 °C | −27 °C |
| | Temperature lapse rate | °C/1,000′ | °C/1,000′ |
| | Wind | 80 kts. | 76 kts. |
| | Wind direction | 210 degrees | 220 degrees |

GENERAL REMARKS: (3)

Flying at 25,000 ft. above 10/10 stratus having tops at 18,000 ft. and below 2/10 cirrus with base at 26,000 ft.
Slight turbulence at first developing slowly to ten minutes of moderate turbulence and stopping quite suddenly after 25 mins. Cloud conditions did not change.

(*Signed*) W. J. CRAIG, Captain.

NOTES: (1) Locality to be given for onset of turbulence (to within 5 miles, if possible.)

(2) This assessment can only be subjective, but the following may serve as a guide:
*Perceptible* $\pm 0.05g$ to $\pm 0.2g$—perceptible difference from rock steady atmospheric conditions, not uncomfortable or alarming.
*Moderate* $\pm 0.2g$ to $\pm 0.5g$—uncomfortable, marked tendency to be lifted out of seat.
*Severe* $\pm 0.5g$ upwards—difficulty in walking about, observing instruments, may be thrown out of one's seat.

(3) These remarks should cover any remarks on the synoptic situation as shown by surface or upper air charts, presence of temperature inversions, marked changes in wind velocity or directions. Also comment on any apparent differences between this type of turbulence and normal convective turbulence as felt by the aircraft.

(4) If details are not known (*e.g.*, Temperature lapse rate) or are in doubt, leave blank.

Fig. 14.
British Overseas Airways Corporation clear air turbulence report.

There is also a possibility that clear air turbulence may be of a less irregular nature than the turbulence normally met, *e.g.* in cloud. The subjective assessment of the crews appears to bear this out as all have reported on the apparent regular, hammering nature of this kind of turbulence. Inspection of the only suitable records (from the Peravia accelerometer) does not altogether confirm the crews' assessment, but this may be because the latter are more sensitive to very small accelerations than the particular instrument employed. The records do show, here and there, that for a period of a few seconds the accelerations may occur at a sensibly constant frequency, which may be as high as 3 per second at a speed of 350 m.p.h. While this frequency is well below the wing fundamental vibration for aircraft such as the Mosquito, it does coincide with the natural frequency for an aircraft with a span of 130 feet[16]. The possibility of a

series of eddies giving rise to accelerations at a frequency coinciding with the natural frequency of a large wing cannot be overlooked. In such circumstances the use of the normal alleviation factor which is based on the concept of single up or down gust becomes misleading, as the lag of the wing in responding to a given series of up and down impulses must be taken into account. On some occasions the effect of a given gust will be aggravated by the wing motion and sometimes it will be reduced. In this light the orthodox "flat topped" gust conception used for design purposes is clearly unrealistic.

When this project was initiated the main problem, so far as a would-be operator of high-speed high-altitude transport was concerned, was that of passenger comfort. How to avoid turbulence, or, if encountered, how to mitigate its effects, were and still are, the main problems of an operator. Complete avoidance of turbulent areas implies a fully reliable forecasting system and it will be clear from the paper that not nearly enough is known at this stage to make this possible. It appears that there is more than one cause of clear air turbulence, but also that turbulence is associated with high rates of wind shear in the vertical and that jet streams are regions where such high rates can be expected to occur. Furthermore, experience shows that turbulent areas are relatively thin, although of considerable horizontal extent.

Stemming from these considerations and from the earlier detailed discussion, the following precepts can be offered to operators and especially to air crews:

(*a*) Avoid flying in areas where jet streams or high thermal gradients in the horizontal are known to exist.

(*b*) Avoid flying within 2,000 feet of the tropopause.

(*c*) If heavy turbulence is encountered assume that one is entering a jet stream and

  (*i*) climb or descend until turbulence is reduced, and/or

  (*ii*) fly at right angles to the local wind direction.

(*d*) Should it appear that wing oscillations are being excited by the turbulence, alter speed as much as possible.

These simple rules are all that can be suggested at this stage, but they should help operators to deal with the worst cases of clear air turbulence.

## 9. CONCLUSIONS

(*i*) The frequency of occurrence of clear air turbulence at high altitude is such as to make it a significant problem from the point of view of passenger comfort. Since the turbulence can be encountered with little or no warning, further research should be directed to establishing a reliable basis for forecasting turbulent areas.

(*ii*) The turbulence occurs in isolated patches of which a representative size is 50 to 100 miles long by about 3,000 ft. thick. It may occur over a wide range of altitude, and there is no evidence that it is associated with any particular topography or geographical position.

(*iii*) Gusts of low and moderate intensity occur at approximately the same frequency at high altitude in clear air as they do at low and moderate altitudes in all flight conditions. On the other hand, severe gusts probably occur much less frequently in clear air at high altitude.

(*iv*) Since severe gusts can occur in clear air at high altitude, the possible implications on design requirements should be examined. Further, the present conception of a "flat topped" gust for design purposes is not realistic, as in practice a turbulent region is characterised by a rapid succession of positive and negative gusts.

(*v*) The available evidence suggests that clear air turbulence occurs in regions of high vertical wind gradient (which is equivalent to a high horizontal temperature gradient) and that the Richardson criterion for turbulence is applicable.

(*vi*) More data are needed before a forecasting technique can be established. It has been found, however, that severe turbulence may be found in a "jet stream" and that turbulence is frequently found near the tropopause.

(*vii*) The results described in the paper were obtained over Western Europe. They do not necessarily apply to other parts of the world.

## ACKNOWLEDGMENTS

Many people and organisations, both at home and abroad have contributed materially to the success of this project, and together

with Mr. N. E. Rowe of British European Airways, the author would like to express wholehearted appreciation of the efforts which have been made. In particular, they would like to offer their thanks to the Flight Department of the College of Aeronautics for their excellent maintenance of two rather temperamental aircraft (amply demonstrated by the fact that virtually no defect occurred while the aircraft were overseas), to the Customs authorities, to the B.E.A. overseas staff and agents, the Meteorological Office, and to the Ministry of Supply without whose financial support this project could not have been undertaken. Above all, they would like to pay tribute to the professional skill, keenness and determination shown by the crew members, Captain T. T. Thomas, D.F.C., Captain D. F. Wilson, Navigating Officer D. L. Jones and Navigating Officer H. J. P. Bower, during the course of the project.

The author is indebted to the British European Airways Corporation and to the Chief Scientist, Ministry of Supply for permission to give this paper (although the opinions expressed are his own responsibility) and would like to thank his colleagues, especially Mr. D. M. Davies, M.A., who was so closely concerned with all the aspects of the project and who made such a significant contribution to it, for their friendly criticism and help.

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## DISCUSSION

**Professor P. A. Sheppard** (Secretary, The Royal Meteorological Society): He thought that he would be representing the feelings of all meteorologists in welcoming very much indeed the first record in literature in Great Britain, and he thought in the world, on the subject of clear air turbulence. He thought that Great Britain had pioneered that work, and it was appropriate that they should hear something of it from Dr. Hislop.

He remembered "encountering" clear air turbulence for the first time in, he thought, 1942. He was then in the Meteorological Office and it fell to him to organise some high-altitude meteorological flights. Prior to 1941 they had meteorological flights in the vertical up to about 24,000 feet as a routine, but nothing above. Then they got some Spitfire flights going to about 40,000 feet, and within a short time began to get pilots'

reports of severe gustiness at cirrus levels. Mr. Absalom, of the Meteorological Office, who was present, would probably remember bringing to his attention one of those early and unexpected reports.

It was important to realise that they had still rather few data. Dr. Hislop had been able to put all the flights on one figure and had then only managed to fill a small part of the area covered by his map. As a sample of the atmosphere taken it was rather small. Indeed if they supposed that in flying along he had got a sample of ten miles across his path—it was difficult to say what representative width could be put to the path—on that sort of basis they found that his 93,000 miles meant that he had sampled an area of the atmosphere of about a thousand miles by a thousand miles, which was roughly only the area of the chart. And yet the atmosphere was with them day by day, so that it was important to realise the extra sampling reqûired before they could be sure of having representative information about it.

As a meteorologist he had been interested in Dr. Hislop's aims, and particularly the second one, "to determine the causes and characteristics of this turbulence." What characteristics had been thrown up in those investigations? They had been told about the occasions when clear air turbulence arose, but he had been looking rather for information about the nature of the gustiness because that might give an idea of how it arose, not merely when it arose, and not merely in what synoptic circumstances. For that reason he had been particularly interested in Table II giving the relative incidence of upward and downward gusts and their relative magnitudes, and there was a very striking feature in that table. It was that the upward gusts occurred at between $1\frac{1}{2}$ times and twice the frequency of the downward gusts. In other words the turbulence which had been investigated did not appear to be uniform. The upward and downward gusts were not equally distributed and that suggested that the turbulence had some characteristics of its own and was rather unlike what they tended to find in other types of turbulence. Could the records given in that table be regarded as representative? It was an important aspect, although he did not know how it should be interpreted.

More "penetrating" instruments were needed for the measurement of the gusts. It was good to have an accelerometer trace but it left much to be desired, since its interpretation was by no means obvious. For that reason he had been interested by the references to other possible methods for investigating the turbulence, such as long vertical smoke trails and other methods which might complement appreciably the sort of information obtained from the flights. He hoped they would find such techniques being brought into the work.

There were two points about the cross-section of the jet stream which Dr. Hislop had shown which he thought might be worth noticing. It was obvious that the region of maximum shear was roughly beneath the centre of the jet, above the line marking the front. That was the region in which maximum shear was expected. In seeking a source for the turbulence it should be remembered that while they had a strong turbulence-producing organism in the shear, they also had in that very region the maximum stabilising action from the vertical temperature gradient for, in crossing the front, they went from cold air to relatively warm air above it. It was not surprising perhaps that the turbulence tended to be rather discontinuous, with the shear sometimes managing to show itself, but the stability tending very much to damp out turbulence when it arose. It was also relevant to note there were very strong shears of wind in the horizontal. The height scale of the figure was much exaggerated, nevertheless they would notice that to the left of the centre of the jet there were wind gradients of the order of 20 m.p.h. per 100 miles and higher values were certainly reached.

He believed Mr. Bannon had investigated clear air turbulence from the aspect of the horizontal wind gradient. There the gravitational control exercised in the first case was no longer operative and so a different criterion for instability was obtained, commonly called Kleinschmidt's criterion, namely, that the horizontal shear should exceed the vorticity given by the vertical component of the earth's angular velocity at the point in question. In middle latitudes the requisite shear was about 10 metres/sec. per 100 km. or, say, 35 m.p.h. per 100 miles, which was of the same order as observed. So there appeared to be two possible sources of turbulence, not necessarily of the same kind, in a jet stream, such as was often, even if not always, associated with clear air turbulence.

**W. Tye** (The Air Registration Board, *Fellow*): His ordinary job in life was to help to ensure safety in civil aeroplanes, and usually they had to work with appallingly little information. Although he thought that everyone in civil aviation put safety as "No. 1" on their list, in fact it was usually much too expensive to find out all they needed to know before the actual operation was upon them. Therefore it was most refreshing to have such a wealth of facts. The information which Dr. Hislop had given was extremely valuable to people working on airworthiness in assessing the magnitude of gust requirements.

He understood that in the actual flying the aim was to find turbulence as quickly as possible (hence the use of the sawtooth procedure) and having found it, to fly in it taking samples. By this method turbulence was presumably met more frequently than in ordinary airline practice. He gathered that in casting the results into their final form allowances had been made so that the final answers were directly comparable to airline practice.

The lecturer had referred to flights in the Comet aircraft and had said in particular that on one occasion the Comet had met a fairly high gust. He had gained the impression that in most of the Comet flying there had been extraordinary freedom from gusts and that if analysed there would be a few of those comparatively severe gusts and almost a complete absence of any below them. Could Dr. Hislop add a little more on that point?

Present-day civil airworthiness requirements included a statement that an aeroplane should be strong enough to withstand a 50 ft. per second gust, when flying at its cruising speed. That requirement had a dual purpose. First of all there was the possibility that in flying in clear air at the cruising speed large magnitude gusts might be encountered unexpectedly. The second underlying thought was that if flying in obviously turbulent air in bad cloud conditions, the pilot would probably reduce speed well below cruising speed; but if the aeroplane were then upset by turbulence it might gain speed during recovery and, before it had finally recovered, it might well have got back to something around its ordinary cruising speed, and at that time it might encounter high velocity gusts. The basic information on which this requirement was drawn up was from *V-g* records, which thoroughly mixed accelerations due to gusts in clear air conditions with gusts encountered in cloudy conditions. There was no possibility of separating the two sources from the *V-g* records. That, perhaps, did not matter so much when the speed of aeroplanes was such that the cruising speed was fairly low and not far removed from the speed at which aeroplanes would fly in severe cloud conditions. With aeroplanes with cruising speeds of 350 to 400 miles an hour they were concerned with the magnitude of the gusts in clear air. These might well be the design criterion because it would be expected that when flying in obviously turbulent conditions in severe cloud conditions, the pilot would reduce speed considerably and thereby alleviate the structural problem. The designer would welcome therefore, for aeroplanes with very high cruising speeds, any alleviation which could be found by reducing the magnitude of the gust velocity corresponding with actual cruising in clear air. Some preliminary thought had been given to this in 1947, when a proposal was made by Great Britain to the International Civil Aviation Organisation, to the effect that if they were justified in assuming that the 50 ft. per second gust requirement was appropriate to applied cloud conditions, then for clear air conditions to be applied at ordinary cruising speed the value of 35 ft. per second could be selected. At the time, that was no more than a guess, but he wondered if Dr. Hislop could say, by reference to Fig. 5, whether something of the order of 35 ft. per second was justifiable.

**Professor A. V. Stephens** (Chairman, Australian Division, Royal Aeronautical Society): He regretted that the lecture had dealt mainly with meteorological matters of which he had no specialised knowledge. It had left in his mind one or two impressions which he suspected were rather ingenuous.

One impression was that clear air was in general perfectly smooth, but that there existed certain isolated regions of turbulence of the order of 50 miles long, of indeterminate width, and perhaps 3,000 feet thick; and that those isolated bits of rough air were composed, he imagined, of eddies something like 100 to 150 feet in extent. That was the picture he had in mind. But he wondered whether that was an accurate picture. Was it not more likely that there were continuous ribbons of turbulence snaking through the

sky? If that alternative picture were correct would not the experiments have given the same results since the exploring aeroplane would have intercepted a ribbon only occasionally?

**Captain D. F. Wilson** (British European Airways): One of the first things that struck him was the very slight degree of bumpiness that was perceptible to the pilot. When flying in the usually smooth air of the upper troposphere or the tropopause, small ripples became quite perceptible although accelerations only of the order of 0.1 *g* were being imposed. In fact, sometimes slight turbulence was reported by the crews which was practically imperceptible on the Peravia trace. With larger accelerations it was found impossible to give an estimation of the degree of turbulence other than under the broad headings of light, moderate or heavy.

Under the category of heavy, the records showed on several occasions that turbulence which was thought to have imposed accelerations above $\pm 1$ *g*, appeared on the trace as having been only in the order of $\pm 0.6$ to 0.7 *g*. It would appear that the seat of the pilot's trousers although sensitive was not capable of reliable estimation of the degree of accelerations imposed on it.

The effect of high altitude turbulence had been described by Captain Thomas as that experienced by a fast car running over some deep, uneven ruts in the road. That, he thought, probably described what was felt as well as anything.

The effect was quite different to what was normally felt when running through convective turbulence at lower levels. The accelerations were of shorter duration but their peaks were much more closely spaced and the aircraft did not seem to "ride" the gusts in the same way. His own first impression was as if the aircraft were battering its way through a series of closely spaced invisible walls. Rapid fluctuations of the A.S.I. needle would take place and although there was usually little movement of the aircraft in the rolling plane, there was often a tendency towards movement in the pitching plane, although that tendency might have been peculiar to the Mosquito aircraft.

The crews seldom experienced any warning of the presence of heavy turbulence and there was no gradual build-up from light turbulence to a large bump. It seemed that either the aircraft was in smooth air or in the thick of the bumps. The captain of a passenger craft would have little time to order safety belts to be fixed and, in consequence, it was possible that passengers moving about the aircraft would lose their footing and be thrown to the floor.

There was one notable exception to that "no-warning" rule, which occurred over the North Sea on flight VR 94. On that occasion, during a descent from 35,000 feet the crew noticed a curious cloud formation at around 25,000 feet. The most remarkable feature of the cloud was a series of corrugations like teeth isolated in clear air. Those "teeth" appeared singly and in groups of two to three and were from 50 to 100 ft. high and some 200 ft. apart. Generally the outlines of those teeth were quite clear and well defined, although in one or two cases the peaks of the teeth appeared to be shrouded in wispy cloud. Quite marked turbulence was experienced on flying through some of the teeth and also in clear air outside of them.

From the pilot's point of view clear air turbulence, as so far experienced, was not likely to be a very dangerous hazard. It was unlikely that a forecast of clear air turbulence would call for cancellations or for a radical change of flight plan, but the effects of the turbulence were sufficiently disturbing to cause them to think twice about flying in it for any long period and he, personally, would welcome any improvement in forecasting technique which would indicate the likelihood of that type of turbulence with greater accuracy than was at present obtained.

**D. J. Lambert** (Vickers-Armstrongs Ltd.): From an aeronautical engineering, rather than a meteorological viewpoint, he thought that the results of the gust research were extremely valuable. He was convinced that one of the ways to produce economic civil aircraft in the future was to ensure that the aircraft structure was designed for the minimum possible loads compatible with safety. There had been a tendency in the past, largely through lack of knowledge, to keep well on the safe side and he thought there was not much doubt that quite a large proportion of the present aircrafts' structures were unnecessarily strong. There was a lot of structure weight to allow for their ignorance of what was really happening in the gusts and he thought more research of that nature, which presumably would be financed ultimately by the taxpayer, would be good for aeronautical progress. It was only by

research such as Dr. Hislop had outlined, that the right loads and the right structural conditions could be found. The frequency of the gusts was probably one of the most important things.

On the whole the results so far were encouraging. The Mosquitos had not encountered gusts which approached the present standard 50 ft. per second design gust and he hoped that in future research would go much the same way.

He gathered that a standard lift curve slope had been used in deriving the accelerations. He did not know much about the performance of the Mosquito but imagined that between 15,000 and 35,000 feet there would be quite a large compressibility variation—probably Mach numbers of the order of 0.5 to 0.6—and it might mean a difference of some five to ten per cent. on the lift curve slope. It would indicate, if a constant lift curve slope had been assumed, that the magnitude of the high altitude gusts had been over-estimated.

Allowing for the difference in areas of the tailplane and the main plane and the difference in their lift curve slopes, he thought that the increment of gust loading on the tailplane would perhaps amount to another five per cent. of the gust velocity, which would apply to the gusts at all altitudes.

The high altitude stall of the aeroplane was important for future design. They might find that with a rather low $C_{L\max}$ under civil cruising conditions, one of the structurally unimportant gusts could cause a stall and although he did not think they would actually be dangerous to aircraft, because there would still be time for recovery, it could be most uncomfortable for passengers.

They had heard quite a lot about the "rough road" effect which the patches of turbulence seemed to have on the aircraft used. He wondered if this effect were all due to the frequency of the gusts or whether it was rather more concerned with the stability and the response of the aircraft to the gusts and whether, in the cases cited, the aircraft used had not responded in pitch and thus the "$g$"s had come and gone rapidly in phase with the changes of vertical gust velocity. Probably this was fundamentally a poor aerodynamic feature and in the future, designs might be expected to have a more rapid response. It was difficult to say whether or not this might result in more uncomfortable runs, but they would certainly need to know more about the rate of build up and frequency of the gusts in those areas of turbulence before they could predict the characteristics of a given aircraft in such conditions.

**Dr. Scorer** (Imperial College): The Richardson criterion itself really was a criterion which told them whether turbulence which was being created would grow of its own accord or not. It had been applied to the case of turbulence created by the ground when the air moved over it, and in one of Professor Brunt's books there were some good diagrams showing that it worked pretty well. There the turbulence was being created all the time by the motion over the ground, and the criterion decided whether it should be damped out or increased, and once increased the first thing it did was to make the lapse rate approach the dry adiabatic. Probably all the gusts had been found at a stable lapse rate so that either the turbulence was only just beginning, or else it was a different thing altogether. Another difficulty about turbulence in free air was that there was no source for initial disturbance as there was in air blowing over the ground. Another suggestion was that atmospheric waves might go through a process of breaking, like water waves. That he thought impossible because air waves did not move over the surface of the earth but were stationary. He was doubtful if any waves had been observed that had been caused by a cold front. They were caused often enough by mountains, but they never moved over the ground and there was nothing like the shelving beach over which they could move which would cause them to break.

It seemed to him that a much more likely explanation of the gusts was that people had been flying through regions where the horizontal velocity was changing rapidly. He had first come across that at Gibraltar where "up" and "down" currents were met by aircraft right down to the ground, and extended for 50 by 50 yd. and so could not possibly be vertical currents. Thus, aircraft came in to land on the runway, touched down and suddenly took off again involuntarily. The obvious explanation was that they came into a region where the horizontal velocity varied and he thought the same thing was going on in the gusts. If they had horizontal variations in velocity that would not upset the stable lapse rate.

The question was how horizontal changes in velocity could occur. First of all a stable

lapse rate was helpful to have because it meant that any turbulence or disturbance of an irregular nature would tend to remain horizontal; whereas if the gusts were at one time vertical and the stability were maintained it would tend to flatten them out, so that horizontal gusts would die out less rapidly.

Secondly, where there was a horizontal temperature gradient they would expect to find it. Here cold air would undercut the warm; any cylinder of air that was rotating would be extended by the process of the cold air under-cutting the warm and because its angular momentum was maintained its angular velocity would be increased. Regions of horizontal velocity gradient would be diminished in size and the gradients greatly increased.

He would expect, although he was not much of a synoptic meteorologist, to find that sort of region east of Newfoundland, as had been suggested, for there air from very different latitudes was brought together. First of all, because it did produce large horizontal temperature gradients, and secondly because it meant that if air were coming from different latitudes in one case its westerly component would be increased and in another decreased, so that there would be a large horizontal shear.

Turbulence in the lee of mountains had often been reported by glider pilots who found turbulence at the lee end of perfectly smooth clouds, which he thought was due to the fact that with a certain amount of mixing a temperature difference across the cloud base would be destroyed. At the downwind end of the cloud where the air was descending the clear air below would be warmed more rapidly than the cloudy air above and static instability would result. That was the only way in which he knew mountains could be responsible for turbulence in clear air. He had only known it reported not far from the mountain top.

**S. Scott Hall** (Ministry of Supply, *Fellow*): It was a matter of great regret that the work had had to be terminated, as Dr. Hislop had indicated, because of economy.

He would like to know what were Dr. Hislop's proposals supposing they were able to resume the investigation? It seemed to him that it would be wiser to wait until they could have an aircraft which had an adequate performance to cruise comfortably in the 40,000 ft. region, rather than to continue the project with an aeroplane such as the Mosquito which, he imagined, was strained to the extreme of its ceiling. Dr. Hislop had not spoken about any difficulties due to that aspect, but he imagined there must have been great difficulty in achieving those results with that aircraft, and he would like to congratulate the flying crews on their work.

The suggestion that the frequency of the gusts coincided with the frequency of a large wing seemed to be a matter of some considerable concern. How serious did Dr. Hislop consider this point to be? What were the implications on aircraft design, and on the design of gust alleviators which so far had been planned on the assumption of the conventional flat-topped guard.

One speaker had said that apart from "moderately severe gusts," he assumed there was a complete absence of turbulence. He had only had one flight of fairly limited duration in the Comet, but he had been interested to note that in fairly clear air at 38,000 feet the aircraft had passed through a patch of mild turbulence. It was difficult for him to describe what it felt like. It was certainly not as severe as a car going over ruts, but there was quite a distinct tremor through the aircraft, which did not seem to agree with the aforementioned assumption.

Dr. Sheppard had said that the first reference he had seen dealing with clear air turbulence had been in 1942. He had noticed recently with interest a quotation in *The Royal Aero Club Gazette* from the writings of that remarkable pilot-author, Antoine De Saint Exupéry, indicating a phenomenon he had encountered which sounded remarkably like clear air gusts. Exupéry must have written this long before 1942.

**N. E. Rowe** (British European Airways, *Fellow*): It had been unfortunate that the work had had to be stopped for, given a little longer time, they might have found out much more. They were then doing horizontal traverses to find out variations of temperature in the horizontal at height, to check some theoretical work of D. M. Davies, linking clear air gusts with high temperature gradients in the horizontal plane and perhaps they might have found out a good deal more in a comparatively short extension of the time.

They had heard the first full report of the results of a new experiment in a field of work

which was still largely unexplored. The experiment was in the best tradition for simplicity and economy of effort. One full-time scientist was engaged with, initially, one crew (pilot and navigator), later increased to two crews when the rate of flying proved too much of a strain for the single crew. The aircraft were on loan from the Ministry of Supply who insured them and supplied all spares. The total cost of two years' work, involving 680 hours of flying and including the cost of bringing the aircraft to full civil C. of A. standards, installing special equipment and so on, was only £53,000, which, he thought, was extraordinarily cheap for experimental flying. He felt that their knowledge of the upper air had been advanced significantly for a small outlay of manpower and money.

The origin of that work, as Dr. Hislop had said, was to find out what went on in the upper air with special reference to the comfort of passengers. In the United States in 1946 he had heard of damage being done to people in a Constellation due to flying into regions of clear air gusts when making a flight across the continent, and it had then seemed to him clear that there was a need for further knowledge, bearing in mind the work that was going on for the development of the turbine-engined aircraft and the fact that they were to fly at great heights. He would like to place on record his gratitude to Mr. K. T. Spencer, who, in response to his suggestion, at once suggested that some work along those lines could be supported by contract.

Dr. Hislop had suggested that it might be necessary to avoid all jet streams, but that might work to their disadvantage in some cases; the regions of high velocity in jet streams might be useful. It was necessary to stress again the importance of forecasting areas of clear air turbulence with reasonable accuracy so that flights could be planned accordingly.

Captain Wilson, who was one of the pilots in the experiments, had made it clear that in the circumstances when he would have said that 1 *g* was being exerted the record showed something a good deal less. That might be, as he suggested, a function of the aircraft, but it was much more likely a function of the rapidity with which those gusts were experienced. They did occur quite rapidly and there had been a number of occasions when they had occurred at three per second; that lined up with what had been said, that small accelerations, if repeated rapidly enough, did give an impression of roughness and real discomfort.

**J. C. Gibbings** *contributed*: Dr. Hislop had investigated both the cause and nature of a serious nuisance. The discovery of associated atmospheric temperature gradients, after further confirmation, might well enable the operator to predict with some certainty the occurrence of those gusts.

Experience would not lead them to expect absolute certainty with such forecasts and thus the aircraft designer was also interested in the nature of the gusts especially as serious wing resonance might be initiated.

It was suggested that the nature (as distinct from the occurrence) of the gust could be investigated most conveniently by using an aircraft whose size was of small order compared with each gust.

Such aircraft, radio-controlled, had been used successfully in America for flight research and as target aircraft.

**J. K. Bannon** *contributed*: Dr. Hislop deduced that the chief cause of clear air turbulence was shear in the vertical which led to a breakdown of smooth flow into eddies in the manner envisaged by Richardson. Investigations in the Meteorological Office of other observations of high altitude turbulence, details of which would soon be published, tended to confirm this conclusion and it seemed that the majority of cases of notable turbulence were associated with small Richardson number. Dr. Scorer's argument that turbulence would quickly reduce the temperature lapse rate from one of static stability to one of neutral stability (adiabatic lapse rate) was not necessarily valid; influences outside the bumpy layer, *e.g.* turbulence in the form of eddies too large or too small to be noticeable in an aeroplane, might be supplying heat to the top of the layer sufficiently quickly to maintain the marked stability usually observed in regions of high altitude turbulence.

There were some instances of clear air turbulence (*e.g.* case VR 27 in Table I), where there was good evidence that the shear in the vertical, measured over a depth of a few thousand feet, was small. Dr. Hislop suggested that the atmosphere was sometimes patchy and that the available observations of shear from radio-sonde measures might not be applicable to the patch of turbulent air

and that there might well have been large shear in the turbulent zone which was not detected by the radio-sonde. This might be so but it might then be asked what influences, on the scale just larger than the size of the turbulent zones, were causing this patchiness with gustiness. Clearly it could not be a general large scale shear in the vertical, for they knew from the radio-sonde observations that this was small.

It was suggested that there were outside forces causing eddies, probably rotating approximately in a horizontal plane (strictly, about an axis normal to the isentropic surfaces), and that those eddies were of a considerably larger size than the eddies which caused bumps to an aircraft — probably several miles across. Durst* had shown that such eddies did exist. Those eddies resulted in fluctuations of the wind at a particular level. It was sometimes observed also that although the wind might be more or less constant with height, it fluctuated about a mean so that although there was little change of wind through a layer of say, 10,000 feet, the wind between might change by 5 knots or so and back again several times. It was suggested that those fluctuations of wind with height were another manifestation of the eddies noted by Durst which were several miles across but might not be very deep. Those fluctuations could, and did, lead to appreciable shear of wind with height over a small depth and it was quite likely that it was in those regions that patchy turbulence occurred of the type noticeable in an aircraft. Those regions of appreciable shear would be patchy also.

It was suggested that those larger eddies of several miles diameter might be caused by shear of the wind in the horizontal. That would explain the part relationship between turbulence and horizontal shear found in the Meteorological Office investigation quoted by Dr. Hislop (Ref. 13). The United Air Lines investigation also found that relation.

Professor Sheppard had suggested that clear air turbulence might be related to an instability set up by a local excess of horizontal shear (anti-cyclonic sense) above the value of the Coriolis parameter. (*See* for example J. S. Sawyer, The Significance of Dynamic Instability in Atmospheric Motions, *Quart. J. Roy. Met. Soc.*, Vol. 75, 1949, p. 364.) In many cases of high altitude turbulence, however, the horizontal shear was cyclonic in sense. This was especially so in cases associated with jet streams. Professor Sheppard's explanation therefore could not be applied to all cases.

Dr. Hislop suggested, tentatively, that the most severe cases of turbulence occurred near jet streams. There had been several incidents recently confirming this view. An aircraft of the Meteorological Research Flight encountered quite severe turbulence (maximum equivalent gust velocity about 21 ft./sec. E.A.S.) at 29,000 ft. in the region of a jet stream on 2nd October 1950. A de Havilland Comet aircraft also met quite severe turbulence on 2nd November 1950 in approximately the same position relative to a well marked jet stream as that in which severe turbulence was met by the same type of aircraft in 1949 (Ref. 6). Again on 7th November 1950 several aircraft over the Midlands and East Anglia found turbulence, variously reported as "violent" or "very severe," at several heights up to 41,000 feet and those incidents were also associated with a sharply defined jet stream.

There was some evidence from those and other instances that, as Dr. Hislop had suggested, turbulence associated with jet streams could have considerable persistence and extend over a considerable space as a long narrow zone along the jet.

It was emphasised that, as Professor Sheppard had said, jet streams as well as being regions of large shear in the vertical were regions of large shear in the horizontal.

It was thought that some of the data in Dr. Hislop's Table I should be accepted only with caution. As he pointed out many of the flights were made over regions where upper air observations were very sparse or non-existent. His estimates of vertical and horizontal shear therefore were made from synoptic charts which, lacking basic observations for their preparation, could not be considered sufficiently accurate for that purpose. Many of those estimates of shears might be misleading.

It should be remembered also that the tropopause surface was not always a continuous surface. It was known that the tropopause frequently was discontinuous, in the form of a step of several thousand feet in height. Such steps were not shown on contour maps of the tropopause surface and it might be that in some cases the steeply

*The Fine Structure of Wind in the Free Air. *Quart. J. Roy. Met. Soc.*, Vol. 74, 1948, p. 349.

sloping tropopause which Dr. Hislop deduced from published charts and associated with turbulence was, in fact, a discontinuous tropopause. There was usually a discontinuity in the tropopause along a jet stream.

**B. K. O. Lundberg** (The Aeronautical Research Institute of Sweden, *Associate Fellow*) *contributed*: The lecturer mentioned that for the determination of the accelerations a recording accelerometer was used, by which the record was obtained in the form of a series of punches on waxed paper. With such a method the work of evaluating the records apparently would take considerable time. At the Aeronautical Research Institute of Sweden, Dr. Gustafsson had developed a recording accelerometer which was designed in such a way that the number of peak and trough accelerations was registered by standard counters. The foreseen range of accelerations was divided into 15 intervals. To each interval belonged two counters, one of which counted the number of peaks within the interval and the other the number of troughs in the same interval. The accelerometer consequently gave directly the frequency of the acceleration peaks and troughs within the various intervals. By means of statistical methods it should be possible to calculate the number of changes in acceleration having a certain mean value and a certain amplitude. This was of great importance for the determination of load programmes for cumulative fatigue tests on aircraft parts.

The first specimen of the F.F.A. accelerometer could not record more than about two peaks per second, which flight tests proved to be too low a frequency. Dr. Hislop had suggested a frequency should be aimed at of at least 8 peaks per second. The accelerometer had since been modified and was now able to record 20 peaks per second. The apparatus was now being tested in flight and the results so far indicated that it functioned satisfactorily.

**G. Arnason** (Chief Meteorologist, Scandinavian Airlines System, Overseas Division) *contributed*: He had the pleasure of listening to Dr. Hislop's lecture on this subject in Stockholm on the 2nd March 1950 for the Flygtekniska Föreningen and had mentioned that at least one of Scandinavian Airlines System's aircraft, when crossing the North Atlantic, had encountered clear air gusts in connection with a jet stream at 21,000 feet.

Dr. Hislop had said the turbulence seemed to be most adequately explained by Richardson's criterion for increase in turbulence:

$$\left(\frac{\partial V}{\partial z}\right)^2 > \frac{g}{T}\left(\Gamma + \frac{\partial T}{\partial z}\right). \qquad (1)$$

It could be assumed reasonably accurate to replace $\partial V/\partial z$ by the thermal wind, which inserted in (1) gave:

$$\frac{g}{T}\,\frac{\partial T}{\partial s}\cdot\frac{1}{2\Omega\sin\phi} > \left[\frac{g}{T}\left(\Gamma + \frac{\partial T}{\partial z}\right)\right]^{\frac{1}{2}} \qquad (2)$$

Solving (2) with respect with $\partial T/\partial s$ gave:

$$\frac{\partial T}{\partial s} = 2\Omega\sin\phi\left[\frac{T}{g}\left(\Gamma + \frac{\partial T}{\partial z}\right)\right]^{\frac{1}{2}} \qquad (3)$$

which was a practical form for discussion and computation of corresponding values of horizontal and vertical temperature gradient.

From those equations it was clear that strong thermal wind was favourable for the creation and maintenance of turbulence, and since the thermal wind was proportional to the horizontal temperature gradient, they might say that great temperature contrasts favoured the same. This led to the conclusion that in the troposphere clear air gusts were most likely to be found in connection with fronts, or frontal surfaces.

The analyses of the twenty cases of clear air gusts observed by the B.E.A. research unit did not confirm this statement, and in one case only was a front directly mentioned. As far as could be seen there was no doubt that the occurrence of the gusts was associated with strong thermal wind, but the observations, together with the analysis, indicated that zones of strong temperature contrasts might have so limited vertical extent that the ordinary signs of a front could not be found on the surface map.

It was not surprising that clear air gusts were not always found in jet streams. Those very strong winds indicated thermal winds of considerable strength but they were the result still more of the fact that the direction of the thermal wind was the same within a very great part of the troposphere. Even if they were justified in considering it more likely that clear air gusts would be found in jet streams than elsewhere, it must be remembered that the thermal wind did not necessarily have to exceed the critical value determined by Richardson's turbulence criterion, and if it did it might be within a zone of rather limited vertical extent.

From equation (3) he had computed the critical value of $\partial T/\partial s$ corresponding to

$\partial T/\partial z = -0.5 \times 10^{-2}$ and $T = 233°$K. and got the values 2.49, 2.85, 3.20, 3.52, 3.82, 4.08 and 4.32 degrees Centigrade per 100 km. for latitudes 30, 35, 40, 45, 50, 55 and 60 respectively. It was difficult to make any statement as to the frequency of occurrence of values of $\partial T/\partial s$ in excess of those, but a brief investigation of average upper air temperature maps published by the U.S. Weather Bureau revealed that in February the mean horizontal temperature gradient at 20,000 feet over eastern N. America was 1/4-1/2 of the critical values given above for the latitudes 30-50. The values measured by the B.E.A. research unit in clear air gusts were at least in some cases between 5.0 and 5.5 degrees Centigrade per 100 km., *i.e.* somewhat in excess of the values given.

It appeared from the results of the B.E.A. investigation that in ten cases of the total of twenty the gusts were encountered near the tropopause. The large temperature lapse rate normally observed just below the tropopause was a reasonable explanation, in particular as strong thermal wind might easily be encountered near the tropopause.

Assuming a lapse rate of 0.8 degrees Centigrade per 100 metres and a temperature of 213°K., equation (3) gave the following values for the horizontal temperature gradient in °C./100 km.: 1.51, 1.73, 1.94, 2.14, 2.31, 2.47 and 2.62 corresponding to latitudes 30, 35, 40, 45, 50, 55 and 60 respectively. Just above the tropopause he assumed isothermal conditions along the vertical and then got the following values from equation (3): 3.38, 3.88, 4.35, 4.78, 5.18, 5.54 and 5.85 for the same latitudes.

The steep slope of the tropopause favoured strong thermal wind above the tropopause. It was of considerable interest to compute the critical slope corresponding to the values given above. Using the known formula

$$\tan\theta_{\text{Trop}} = -\frac{\left(\frac{\partial T}{\partial s}\right)_{\text{below}} - \left(\frac{\partial T}{\partial s}\right)_{\text{above}}}{\left(\frac{\partial T}{\partial z}\right)_{\text{below}} - \left(\frac{\partial T}{\partial z}\right)_{\text{above}}} \quad (4)$$

the following critical values for the slope had been computed: 0.61/100, 0.72/100, 0.79/100, 0.87/100, 0.94/100, 1.00/100 and 1.06/100 corresponding to the same latitudes as before. If the slope of the tropopause were less than the critical value $\partial T/\partial s$ above the tropopause would also be below its critical value. The special case that $\partial T/\partial s_{\text{below}}$ was zero gave the following critical values for the slope of the tropopause: 0.42/100, 0.49/100, 0.54/100, 0.60/100, 0.65/100 and 0.73/100.

From those facts they might be inclined to draw the conclusion that clear air gusts were more frequent above the tropopause when $\partial T/\partial s_{\text{below}}$ was very weak, but they should bear in mind that there probably was a rather high positive correlation between the slope of the tropopause and $\partial T/\partial s_{\text{below}}$ just as there was a high positive correlation between strong thermal wind and small vertical temperature gradient in frontal zones.

From those consideration it would appear that detailed investigation of the horizontal temperature gradients occurring in the atmosphere was most essential for a successful forecasting of clear air gusts, and it was believed that available meteorological material was sufficient to provide the knowledge and understanding needed for a forecasting on a trial basis.

**K. H. Larsson** (Canadair Ltd., formerly Chief Engineer, AB Aeotransport-Swedish Air Lines) *contributed*: In general he thought that airline people had been somewhat disappointed to learn that altitudes of 25,000-30,000 feet, where they would, no doubt, be operating regularly within the next five years, did not provide such a smooth highway as they had thought in the past. The "tropopause" especially seemed infected with extremely high winds ("jet streams") and air turbulence. He wished they could have coined a better word than "jet streams," which must necessarily be interpreted by the public as having something to do with "jet aeroplanes."

The fact that those winds reached speeds of 150 m.p.h. or more and were difficult to predict, would tend to delay their use of the upper atmosphere for fast turbo-jet transports because of the large quantities of reserve fuel that must be provided. The existence of clear air turbulence seemed to be almost of secondary importance in that connection.

True, they had heard of maximum vertical gust velocities of the order of 30 ft./sec., which certainly could not be ignored when they were flying at speeds of 500 m.p.h. or more.

But it seemed to him that the localised character of the turbulence put it in the same category as icing conditions, which by now they had largely learned to master.

He had no doubt, therefore, that by reporting such turbulent areas and by

improved weather forecast techniques they would be able to keep out of the worst trouble from this source.

## DR. HISLOP'S REPLY

**Professor Sheppard:** He agreed that the sample of 92,300 linear miles was small enough, but when considered as an area of perhaps $10^6$ square miles and compared with the area of the earth and the daily change of weather, it was a very, very small sample indeed. Yet it could not be considered as totally insignificant as they had to start somewhere; and it was best to do so modestly with a flexible organisation, in order to take advantage of growing knowledge and advancing technique.

Professor Sheppard had drawn attention to the relative frequency of the up and down gusts and had asked, "Was the difference significant?" On balance he thought it was not. He did know that one of the accelerometers which they were using had a slight bias in the positive direction. It was small, but it might have influenced the results and that was why he had preferred to neglect the difference between up and down gusts and use the *sum* of positive and negative gusts in the statistical analysis. In that he was fortified by general experience from other records of turbulence (not necessarily in clear air), obtained from many other sources. On balance they all appeared to indicate that the relative frequency of occurrence of up and down gusts was equal. Possibly the physical picture of what was going on might also influence the view.

The point about turbulence being occasionally discontinuous was one which had often impressed him during the investigation. He had a mental picture of the forces inducing turbulence overcoming those resisting it, building up the turbulence which then dissipated its energy, thus tending to die out. A fresh cycle then began anew. Only when conditions were particularly favourable was the turbulence likely to be continuous for long stretches either of time or distance.

The Kleinschmidt criterion mentioned by Professor Sheppard was a new one to him, at least in name. He felt sure that clear air turbulence could be caused by more than one set of meteorological conditions, and that only the heaviest turbulence could be attributed with reasonable certainty to wind shear in the vertical. This was borne out by those results where slight to moderate turbulence was reported in the absence of marked wind shear in the vertical (*see* Table I). The possibility that wind shear in the horizontal could induce turbulence was doubtless real, although he understood from Mr. Bannon that attempts at correlation were not entirely satisfactory. More results would be required, together with a fuller theoretical explanation, before the horizontal shear criterion could be established.

**Mr. Tye:** Mr. Tye was correct in inferring that, by virtue of the particular technique adopted, turbulence was encountered more often in a given height range by the Mosquito than by an aircraft flying straight and level in that height band. But, bearing in mind how the size and thickness of turbulent layers varied—and this had an important bearing on the effectiveness of the search technique—and also that turbine-engined aircraft would probably be operated on a gradual climb and descent, as opposed to steady level flight as at present, then the importance of the increased chances of meeting turbulence lost significance. Figs. 3-6 were plotted on a logarithmic scale, and even if the miles to fly were doubled it would not alter the picture radically. Rather than introduce a complex and arbitrary correction factor in distance, he had preferred to use the actual distance flown by the Mosquito in analysing the results.

He had not obtained any complete statistical picture from the Comet trials, but such data as was available did not suggest that the clear air turbulence experience of that aircraft was confined to a single instance of very severe turbulence. The lack of data was to be regretted, but no doubt the pressure on the firm to obtain a large amount of information on a wide variety of essential points was very great. It was clearly difficult to cater for all the demands. By arrangement with B.O.A.C., they hoped to get a great deal of useful recordings from the Peravia accelerometer to be installed on the B.O.A.C. development trials of the aircraft.

Mr. Tye had asked, "Was 35 ft. per second all right as a design standard for clear air turbulence?" They had measured a maximum of 26 ft. per second and the data suggested that it could be extrapolated with reasonable assurance to about 35 ft. per second. There was also evidence that gusts of about 35 ft. per second had been met over Europe. Therefore he would be inclined to say that 35 ft. per second was too low. The

aeroplanes to which those conditions were applied were liable to fly anywhere over the world, and thus the weakness of the small sample had to be remembered. There might be more intense jet streams elsewhere, for example.

**Professor Stephens:** He thought that, on some occasions, Professor Stephens' concept that there were not necessarily separate areas of turbulence, but that there were possibly ribbons of turbulence wandering about in the upper air might be right and the aircraft merely crossed the ribbon from time to time, thus giving rise to the impression of a turbulent patch.

They had recognised this possibility and the technique of exploring a turbulent area had been amended so that when, on determining the horizontal extent of turbulence, the aircraft ran out of turbulence into still air, then a rapid exploration in the vertical was done to check whether the turbulence had actually ceased. It was not always possible to execute this technique, but on the whole they were fairly confident that in most cases the extent of that area of turbulence had been reasonably well assessed.

In the case of turbulence associated with a jet stream, a lot depended on the position and direction of the axis of the jet stream. A really good example was in the Comet incident already referred to in Ref. 6. On that day turbulence had been encountered by several aircraft roughly along a line running north to south over a distance of about 1,000 miles. There was a slight variation in height over the length, suggesting that the jet stream axis was not horizontal.

He would like to correct Professor Stephens' picture in one minor respect. The representative horizontal dimension *in any direction* was about 50-100 miles, not merely in one direction. Naturally, this was subject to very wide variation at this early stage of knowledge (*e.g.* Ref. 6), but it was sufficient to place the matter in perspective.

**Captain Wilson:** He had given a very graphic picture of what the crew felt subjectively, and his contribution to the discussion would be most valuable from the pilot's point of view. The occasion when wisps of cirrus seemed to hang in clear air was interesting. In his view a possible cause was the existence of turbulent "cells" of air which became visible by virtue of the transfer of a body of air at one temperature to another lower temperature level, thus causing the moisture present to condense and become visible as cloud. He understood that this process gave rise to the type of cloud sometimes known as altocumulus - castellatus ($C_m$ 8), and it seemed possible that a similar mechanism could exist at cirrus levels.

**Mr. Lambert:** In an investigation of this nature, they could not lay claim to a very high degree of accuracy. He would think that the order of error in the quoted miles to fly per gust might be about $\pm 25$ per cent. or even more. At first sight this might suggest that the results were all rather crude, but such matters had to be viewed in true perspective. Figs. 3-6 showed that an error of this order could not influence the general results to any marked degree. In the circumstances, therefore, it was justifiable to ignore the small errors which might be introduced by omitting the effect of Mach number on lift slope and the contribution of the tailplane to lift.

It was highly likely that the aircraft did not respond in pitch to the general run of gusts met in clear air and that this lack of response would contribute to the characteristics felt by the crews. When a 500 m.p.h. aeroplane was considered, the chances seemed rather remote of designing it to respond to gusts occurring perhaps twice per second and still keep satisfactory flying qualities in other conditions of flight.

**Dr. Scorer:** In his original paper,[11] Richardson appreciated that the wind gradient necessary to sustain and increase turbulence at normal low altitude conditions was only about half that likely to be needed at the base of the stratosphere. Yet in his mind this did not preclude the existence of ordinary atmospheric eddies at such heights. To quote: "We then conclude that the usual source of atmospheric eddies is in the first few hundred metres and that they may sometimes be found at the base of the stratosphere." He thought it would be surprising if, in those vast rivers of high speed air blowing at great heights, some little turbulence did not exist here and there. All that was needed to develop them into much larger and heavier turbulent areas, was the right atmospheric conditions.

The suggestion that sudden changes in horizontal velocity could cause enough change in lift to give severe bumps, could easily be discounted by considering the numerical values involved. Reverting to equation (1) and taking the partial derivative

of the increment in acceleration with respect to vertical gust velocity

$$\frac{\partial \Delta n}{\partial U_e} = \frac{\rho_o K a V_i}{2w} \quad . \quad . \quad (5)$$

Now, considering the usual equation for lift, and the relationship between lift and weight

$$L = \tfrac{1}{2}\rho_o V_i^2 S C_L$$

and

$$L = nW$$

(where $S$=wing area, $C_L$=lift coefficient, $W$=weight, $n$=acceleration in $g$ units, and $\Delta n = n - 1$)

Then, again taking partial derivatives,

$$\partial L / \partial V_i = \tfrac{1}{2}\rho_o S C_L \cdot 2V_i$$

Hence

$$\frac{W \partial n}{\partial V_i} = \tfrac{1}{2}\rho_o S C_L \cdot 2V_i$$

and

$$\frac{\partial n}{\partial V_i} = \frac{\partial \Delta n}{\partial V_i} = \frac{2}{V_i} \quad . \quad (6)$$

This gave the increment in acceleration caused by a virtually instantaneous change in horizontal air speed, such as might be caused by a horizontal gust.

Assume a representative case for an aircraft such as the Mosquito, namely: $\rho_o = 2.38/10^3$, $K = 0.7$, $a = 4.5$, $w = 45$, $V_i = 340$ ft./sec. Then, applying this to equation (5)

$$\partial \Delta n / \partial U_e = 0.0255$$

In equation (6)

$$\partial \Delta n / \partial V_i = 0.0059$$

For those conditions, a vertical gust was about 4 times as effective in causing a given vertical acceleration as a horizontal one of the same magnitude. To cause accelerations of about $\pm 0.5$ $g$ occurring 2 or 3 times a second would call for horizontal gust velocities varying in magnitude over $\pm 85$ ft./sec. (indicated velocity) in about 200 feet. This scarcely seemed to be a likely state of affairs.

Furthermore, experience showed that the accelerations felt could be reduced by slowing down the aircraft. This fitted in with the vertical gust concept, whereas if horizontal gusts were the cause the reverse would be the case.

Dr. Scorer was a little unwise in being guided by experience at Gibraltar. The local surface winds at that aerodrome were notoriously fickle and even dangerous in certain ambient directions, because of the eddies shed by the large mass of the Rock looming over the runway. An aircraft coming in to land was more sensitive to changes in horizontal velocity of the air than when in cruising flight, and although the vertical accelerations imposed on the aircraft were small, their importance was enhanced because of the proximity of the aircraft to the ground. Even a few feet of displacement from the chosen path at this stage might end in trouble.

Therefore he had no compunction in dismissing the possibility of horizontal gusts causing the observed accelerations.

It was not necessary for a sea wave to have a shelving beach on which to break. "White horses" were commonly observed in deep water if the wind were at all fresh. Might not the same considerations apply to atmospheric eddies?

**Mr. Scott Hall:** He would be pleased to discuss proposals for future work with him on any occasion as they had pretty clear ideas of what form future work should take. They would like to have Canberra aircraft because they would obtain adequate performance, and the technique could be made to suit the range of this type of aircraft. It was true that the Mosquito was the only suitable aircraft available in 1947 when the project started, and it was rather significant that, when looking then for an aircraft with a practical range of a thousand miles or more, capable of getting to 35,000 or 40,000 feet and with a good high speed performance, they had to go to a 1940 design for it.

The limitations of stability and control at 37,000 feet were the real reasons why they had to lower the upper limit of their "sawteeth." After a time it became a struggle to get the aeroplane up from 35,000 feet to 37,000 feet and they felt that the time spent in the last two thousand feet, with the engines tearing their hearts out, was not worth the results. They had lowered the height with good effect on the serviceability.

Considering the question of the natural frequency of the wing and how it would respond to a series of gusts occurring at this frequency, he could understand Mr. Scott Hall's alarm. It was most unfortunate that, despite special instruments being carried expressly to give reliable data on the frequency of occurrence, they had had to rely on the rather slow-running Peravia instruments for such data as was available. For that reason, he thought that, pending more

reliable and accurate data on the rate of build-up of gusts and the numbers likely to be encountered at a quasi-steady rate, then the position could only be watched. In the meantime, he would like to suggest that the case of an aircraft wing (100 feet or more span) meeting a train of, say 10 gusts of $\pm 20$ ft./sec. occurring at the natural frequency of the wing, be examined. He did not know whether the wing could take such a loading case. It might be perfectly capable of doing so, and he for one would be glad to know that it could.

Mr. Scott Hall's reference to St. Exupéry's writings had awakened his own memory; he had looked through "Wind, Sand and Stars" once more to find that the incident referred to took place in a gap through the Andes. Undoubtedly the author was describing turbulence occasioned by high winds blowing over mountains. St. Exupéry's reaction to clear air turbulence was of very great interest in that he expressed so vividly its—to say the least—disconcerting nature. "Give me a good black storm in which the enemy is plainly visible. I can measure its extent and prepare myself for its attack. I can get my hands on my adversary. But when you are flying very high in clear weather the shock of a blue storm is as disturbing as if something collapsed that had been holding up your ship in the air. It is the only time when a pilot feels there is a gulf beneath his ship." (Chapter IV.)

To find a reference to the problem enshrined in some of the finest flying literature ever written was most stimulating.

**Mr. Rowe:** He was glad that attention had been drawn to the relatively low total cost of the investigation; from enquiries made elsewhere, he believed that their costs were about as low as could have been achieved anywhere on this class of research work, which was naturally very expensive. To a very large extent he attributed it to the use of a small flexible organisation of scientists and air crews, grafted on to an existing maintenance organisation already engaged on experimental flying, thus achieving a most happy arrangement.

**Mr. Gibbings:** The suggestion to use a small pilotless aircraft to investigate the gust structure brought up a question which had always been in their minds when pursuing this gust research. That was whether an orthodox aeroplane was the best tool for such work. The drawback of any one device was that it filtered the spectrum of turbulence according to its design. However, a small, lightly loaded pilotless aircraft would have considerable advantages in helping to determine the gust structure, and the pros and cons of such a tool should be weighed carefully. Considerable complication in the experimental technique would certainly result, and there would arise the question of correlating and comparing the results with those felt by a passenger aeroplane. Nevertheless, the suggestion was valuable.

**Mr. Bannon:** He had been interested and encouraged to hear that recent evidence from independent Meteorological Office investigations confirmed the general association of turbulence and a low Richardson number. Also that their evidence showed severe turbulence to be associated with sharply defined jet streams.

If it were accepted that wind shear in the vertical was an important consideration, then there was the difficulty of getting reliable evidence of shear when the turbulence was slight (*e.g.* VR 27). With all due respect to the Meteorological Office, he could not help but feel that, excellent though the radio-sonde network was over Great Britain, the data available could not be applied with very great confidence to places a few hundred miles away from the point of ascent, and distant perhaps 6 or even 12 hours in time, especially when winds were not very high. According to the Daily Weather Report for 6th July 1948 (the date of VR 27) the nearest upper air observations available were at Downham Market in East Anglia, some 300 miles away, and a considerable variation in strength with time had taken place. It was not impossible that the local shear in the vertical had taken place over Heligoland later that day, possibly by virtue of the existence of a mechanism such as suggested by Mr. Bannon.

Mr. Bannon was correct in suggesting caution in interpreting the wind shear values given in Table I. It was because of the weakness of the results in that respect that earnest thought was given to measuring wind shear directly from the aircraft. The fact that an upper air chart could be interpreted as depicting a steeply sloping tropopause, whereas it might conceal a discontinuity in the tropopause, was a point to be watched.

The great interest taken in Sweden in the work was very gratifying, and he had given three lectures in Sweden in March 1950 on

the topic. The subject matter covered in those lectures was much the same as that of the present lecture, although less extensive and, as actual flying had only just ceased, the results were not fully analysed at the time. Therefore he was particularly glad to have the written contributions from Sweden.

**Dr. Lundberg:** Without details of the instrument mentioned, it was not possible to make a critical appraisal of its ability to meet the pressing need for a counting accelerometer for work of this nature, but it certainly seemed very promising.

He noted that the counting frequency had been increased from the original two to twenty per second and thought that this would be more than adequate to deal with clear air turbulence, even if encountered by extremely high speed military aircraft. Whether or not it might inadvertently pick up severe vibrations from power plants was a design matter which might have to be attended to. He would look forward to hearing how it behaved in actual practice.

**Mr. Arnason:** It was interesting that Mr. Arnason also considered that marked temperature gradients in the horizontal were of great importance in deciding whether or not turbulence was likely to be sustained. When analysing the results from the B.E.A. voyages, a close examination was made of all data for signs of a marked upper air front, but without very satisfactory results. Part of the trouble lay in the paucity of reliable upper air observations over Europe; this drawback had to be accepted when planning their flights.

It was rather doubtful whether sufficient information existed on the correlation of horizontal temperature gradient and turbulence to start making forecasts with reasonable success. More experimental traverses through turbulent air, paying particular attention to this point were needed.

At this stage they could not say that any results were available which would be of real value in confirming (or otherwise) whether the magnitude of turbulence above the tropopause was related to the horizontal temperature shear below the tropopause. An aircraft with better performance than the Mosquito, coupled with more results, would be needed to verify this point.

**Mr. Larsson:** He was right in assuming that the presence of jet streams would complicate the operation of high speed passenger transport aircraft. Whether or not clear air turbulence was of secondary importance compared with the jet streams depended on operating experience in the 25,000-45,000 feet height range over the major air routes of the world. The bulk of this experience had still to be gathered. In some areas it was felt that the problem might be rather more acute than he suggested, owing to the intensity and extent of the turbulence which might be encountered. Also, jet streams might sometimes help an aircraft, but turbulence never could.

A great deal could be done towards setting the problem in its true perspective in the various areas of the world by ensuring that an adequate reporting procedure was followed by airlines operating fast, high altitude machines and that the results were systematically analysed. The reporting form now under consideration by I.C.A.O. should meet a vital need in this respect.

# DEFINITION AND MEASUREMENT OF JET ENGINE THRUST

by

BENGT JAKOBSSON, Dr.Sc. (Eng),* A.F.R.Ae.S.

SUMMARY

In this paper the thrust of the turbo-jet engine is rigorously defined, and is divided into the three components front external, internal and rear external. The measurement of thrust in static tests and in flight is discussed. Current methods are critically examined and test methods are proposed. Special attention is given to a method of calculating flight performance from simple static tests with different nozzle areas. A convenient form of engine curves for static tests is shown and a method of flight testing is given.

## INTRODUCTION

During the past decade jet propulsion has become normal practice for high-speed aircraft. Everyone in the aircraft field is well acquainted with the new type of engine and its possibilities, but when trying to make rigorous theoretical studies it is found that in some cases certain distinctions must be made and certain quantities need to be thoroughly clarified.

It may seem unnecessary now to define the thrust of the jet engine after it has been used successfully for some years, but it will be shown that to avoid mistakes the thrust must be defined in a new way. It will also be shown how the thrust can be divided into three components of special importance to the engine and aeroplane designer. Once the thrust has been defined, a rigorous method must be laid down for its measurement in ordinary static test beds—even if this static thrust is of little value in obtaining flight data for the aircraft. More important than the static thrust is the flight thrust, which is difficult to measure in flight. To determine flight thrust the Germans used the Munich plant, and the Americans now have several altitude plants either working or under construction. It is the author's opinion that the thrust as measured in altitude plants is of little value unless it is obtained from full-scale tests of aircraft with completely representative engine nacelles.

In this paper a simple and economical method is suggested for obtaining flight thrust from normal static tests by using the laws of similarity. From a new system of curves for a particular engine, a few simple flight test results give the actual thrust.

Test values for jet engines are often converted to values at a total temperature of 288°K and a total pressure of 14.7 lb./in.² at the intake. These values are usually called *corrected values*. It is now proposed that *correction* should refer only to instrument errors. Values at 288°K and 14.7 lb./in.² are referred to as *normalised values*. Values under flight conditions corresponding to the standard atmosphere are called *standardised*. *Nominal values* are defined in Section 2.2.

### NOTATION

| | |
|---|---|
| $A$ | area (ft.² or in.²) |
| $B$ | fuel consumption |
| $b$ | specific fuel consumption |
| $C_D$ | drag coefficient |
| $d$ | diameter |
| $F$ | thrust (lb.) |
| $f$ | "function of" |
| $g$ | acceleration due to gravity (=32.2 ft./sec.²) |
| $H$ | height (ft.) |
| $J$ | mechanical equivalent of heat (1,400 ft. lb./C.Th.U.) |

Paper received March 1950.

Dr. Jakobsson is Performance Engineer, Svenska Flygmotor Aktiebolaget.

| | |
|---|---|
| $k$ | a factor in Section 4.1 |
| $k_p$ | specific heat at constant pressure |
| $M$ | Mach number, based on static temperature |
| $M'''$ | Mach number, based on total temperature |
| $n$ | engine speed (r.p.m.) |
| $p$ | pressure (absolute pressure) (lb./in.²) |
| $p'''$ | total pressure |
| $p''$ | static pressure |
| $Q$ | mass flow (lb./sec.) |
| $q$ | dynamic pressure, $\frac{1}{2}\rho v^2/g$ |
| $R$ | gas constant |
| $T$ | temperature (°K.) |
| $T'''$ | total temperature |
| $T''$ | static temperature |
| $t$ | temperature (°C.) |
| $v$ | velocity (ft./sec.) |
| $x$ | velocity ratio, $v_1/v_0$ |
| $\gamma$ | ratio of specific heats |
| $\eta$ | efficiency |
| $\theta$ | temperature ratio, $T_2'''/288$ |
| $\rho$ | specific density (lb./ft.³) |
| $\Phi$ | pressure ratio, $p_2'''/14.7$ |
| $\varphi$ | pressure function |
| A.F.C. | actual flight conditions |
| N.F.C. | normalised flight conditions |
| S.T.C. | static test conditions |

*Suffixes*

| | |
|---|---|
| B | balance |
| c | combustion |
| d | diaphragm |
| FE | front external |
| I | internal |
| k | general symbol for station number |
| n | nominal |
| RE | rear external |
| r | ram |
| 0, 1, 2.... | station number or function number |

## 1. DEFINITION OF JET ENGINE THRUST

### 1.1. General

The jet aeroplane in flight is concerned with two gas streams. The outside stream is air and the inside stream is air at the intake and combustion gases at the exit. The inside stream is called here the internal or engine air flow. The work done by the engine gives an increase in momentum of the internal air and the drag of the aeroplane gives an equal decrease in momentum of the external air. The thrust of the engine is defined as this momentum increase of the internal air.

The reference plane in front of the engine is usually placed "at infinity" before the aeroplane (Station 0 in Fig. 1) where the pressure is equal to the atmospheric pressure. The reference plane behind the engine is sometimes chosen as the exit, Station 3, and sometimes as Station 5, where the pressure of the internal air is again equal to atmospheric. The streamlines *AB* and *CDE* represent border lines between the internal and external air flows.

The formula for the thrust (net thrust) in the two cases is (*see* Notation)

$$F = -\frac{Q_0}{g}v_0 + \left[\frac{Q_3}{g}v_3 + A_3(p_3 - p_0)\right] \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$F = -\frac{Q_0}{g}v_0 + \frac{Q_5}{g}v_5 \quad . \quad . \quad (2)$$

The first term on the right hand side is the intake drag; the second is the gross thrust. Equation (1) is the more usual and the pressure $p_3$ is assumed equal to $p_0$ when the velocity $v_3$ is subsonic.

Before giving a more rigorous definition of the net thrust the different parts of the flow from Station 0 to Station 5 are examined.

The force

$$F_k = (Q_k/g)v_k + A_k(p_k - p_0)$$

is called "the thrust at Station $k$."

### 1.2. Front External Thrust

Between Stations 0 and 1 the speed is changed from $v_0$ to $v_1$ (considered here as a deceleration) and the pressure on the surface *AB* builds up to $(p_0 + \varphi)$, where $\varphi$ varies from *A* to *B*. The equation for longitudinal equilibrium of the internal air between *A* and *B*, in terms of one dimension, is

$$(Q_0/g)v_0 + A_0 p_0 + \int_{A_0}^{A_1} (p_0 + \varphi)\,dA - (Q_1/g)v_1 - A_1 p_1 = 0$$

which gives

$$\int_{A_0}^{A_1} \varphi\,dA = -(Q_0/g)v_0 + [(Q_1/g)v_1 + A_1(p_1 - p_0)]$$

or

$$\int_{A_0}^{A_1} \varphi\,dA = -F_0 + F_1 \quad . \quad (3)$$

The integral on the left hand side is the

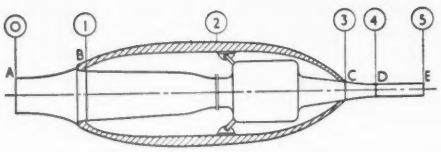



Fig. 1.

front external thrust $F_{FE}$ relative to the outside air, and

$$F_{FE} = -F_0 + F_1 .$$

With the notation

$$\left.\begin{aligned} x &= v_1/v_0 \\ v_0 &= M'''\sqrt{(g\gamma RT_0''')} \\ T_0''' &= T_0'' + v_0^2/(2gJk_p) \end{aligned}\right\}$$

where $M'''$ is flight Mach number based on the total temperature at the engine intake, the following formula is obtained

$$\frac{F_{FE}}{F_0} = x\left\{1 + \frac{[1-\tfrac{1}{2}(\gamma-1)(M'''x)^2]^{\gamma/(\gamma-1)} - [1-\tfrac{1}{2}(\gamma-1)M'''^2]^{\gamma/(\gamma-1)}}{\gamma(M'''x)^2[1-\tfrac{1}{2}(\gamma-1)(M'''x)^2]^{1/(\gamma-1)}}\right\} - 1 \quad . \quad (4)$$

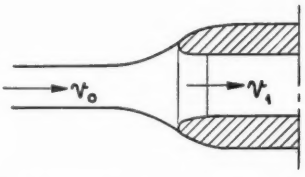
Curves of this ratio for $\gamma = 1.40$ are given in Fig. 2. The Mach number $M'''$ of equation (4) is replaced in Fig. 2 by the flight Mach number $M$, based on the static atmospheric temperature $T_0$. $F_{FE}$ is usually positive.

For incompressible flow equation (4) is simply

$$F_{FE}/F_0 = (1-x)^2/(2x) .$$

The front external thrust produces an aerodynamic loading on the outside of the nacelle, most of which is probably on the lips of the intake. The value of this loading is $F_{FE}/q$, where $q = \frac{1}{2}\rho v_0^2/g$. It has been found in wind tunnel tests that speed ratios $x$ less than 0.30 or 0.40 increase considerably the drag o fthe aeroplane (*see* Ref. 5).

At supersonic values of aircraft speed there are one or more shocks at the intake. If the area $A_1$ is ideal, the engine sucks in all the air in front of $A_1$. Then in Fig. 3*a* there is a normal shock at $A_1$, and the front



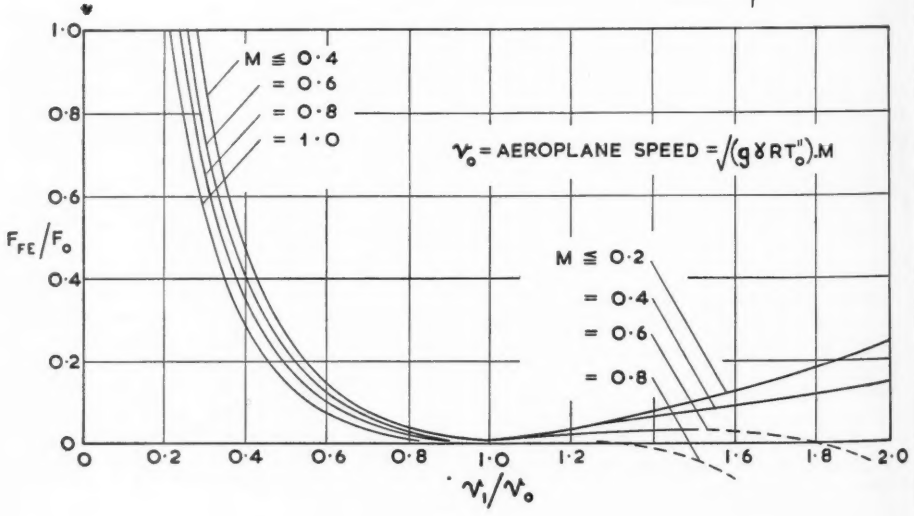




Fig. 2.

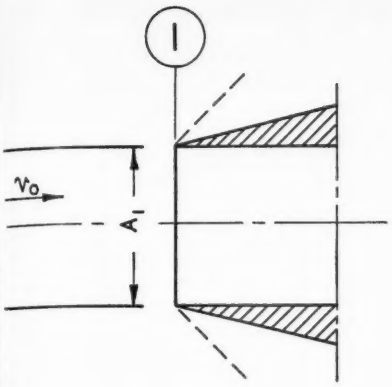



Fig. 3(*a*)

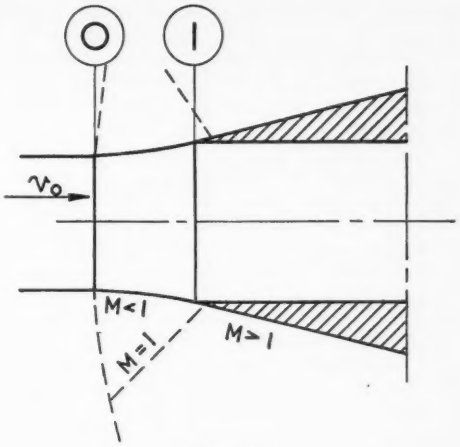



Fig. 3(*b*)

external thrust is zero. If $A_1$ is larger than the ideal, there will be a detached shock as in Fig. 3*b*. The shock for the internal air is approximately normal. The shock defines Station 0. The air at the intake is then subsonic, and there is an ordinary front external thrust.

The relative size of the ideal intake area $A_1$ in a typical case is shown in Table I for different heights and flight Mach numbers, based on static temperature $T_0''$. With $A_1=100$ this engine at $H=0$ and $M=1.4$ would give 13 per cent. of its total thrust as front external thrust.

### 1.3. Internal Thrust

If the atmospheric pressure surrounds the engine between Stations 1 and 3, there is a force $F_I$ acting in the mountings of the engine and ducting. For longitudinal equilibrium

$$(Q_1/g)v_1+A_1\,p_1+F_I-(Q_3/g)\,v_3-\\-A_3\,p_3-p_0\,(A_1-A_3)=0$$

which gives for the internal thrust $F_I$

$$F_I=-F_1+F_3 \quad . \quad . \quad (5)$$

This is in good agreement with equation (3).

TABLE I

IDEAL INTAKE AREA

| *Height* | *Flight Mach number* | |
|---|---|---|
| | 1.0 | 1.4 |
| 0 | 81 | 76 |
| 40,000 | 100 | 94 |

### 1.4. Rear External Thrust

#### 1.4.1. *At subsonic exit pressure ratio*

Up to the present it has been generally supposed that the static pressure at the exit of the engine is equal to atmospheric under subsonic conditions. But this is not absolutely true. When the external and internal air meet at Station 3, there will be a mutual inter-action (Fig. 4). The external air, flowing towards the axis of the jet, will contract the jet and make $p_3$ higher than $p_0$. At Station 4 the internal air will have expanded to a pressure $p_4$ equal to the atmospheric $p_0$. The flow from Station 3 to Station 4 will be accompanied by losses and mixing of the internal and external streams. It seems that the process from Station 3 to Station 4 could be treated with sufficient accuracy as an adiabatic-isentropic non-mixing flow.

With this assumption the reasoning of Section 1.2 is valid and Fig. 2 still applies. The rear external thrust is

$$F_{RE}=-F_3+F_4 \quad . \quad . \quad (6)$$

which in the subsonic case is negative and produces a loading most of which is at the lips of the exit.

Because of the geometry of the external flow path the strength of inter-action will be different and the velocity ratio $v_0/v_3$ between external and internal air will be important. As $v_0$ increases, this ratio will increase from, say, 0.2 to 0.5. At 0.5 the jet contraction should be larger than at 0.2. The rear

external thrust at high engine speeds will usually be very small, but the effect is important in that the engine works against a smaller exit area $A_4$, which implies not only larger thrust but also, higher turbine temperature.

The criterion of a jet contraction is a static pressure $p_3$ higher than $p_0$. These higher pressures have been found in some jet aeroplanes, and the numerical values are in agreement with theory. In one case the thrust seemed to be 3.5 per cent. too high. Calculation showed that this increase could result from a static pressure at the exit of 28 in. of water. The diameter $d_4$ would equal 0.987 $d_3$, which is a very small contraction. But the turbine temperature increase would be 25°C., which cannot be ignored. The measured exit pressure in a similar case was 24 in. of water.

### 1.4.2. *At supersonic exit pressure ratio*

#### 1.4.2.1. *With minimum external air inter-action*

With a supersonic exit pressure ratio Station 4 is again the position of minimum area of the internal air flow (Fig. 5). The velocity at Station 4 is sonic and $p_4$ is greater than $p_0$. If there is no inter-action with external air flow after Station 4, the well known Prandtl-Meyer-flow will exist from Station 4 to Station 5. Theoretically the jet will never reach the atmospheric pressure.

For every Station 5 after Station 4, however, the following equation is true

$$(Q_5/g)\,v_5+A_5\,(p_5-p_0) = (Q_4/g)\,v_4+A_4\,(p_4-p_0)$$

and therefore $F_5=F_4$.

This is treated by Ferri[4].

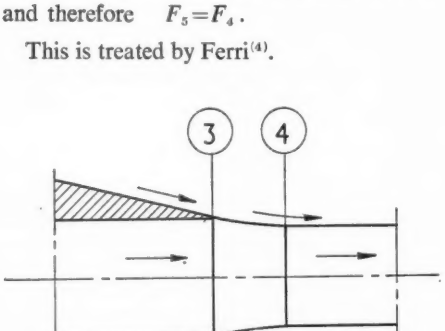



Fig. 4.

#### 1.4.2.2. *With maximum external air inter-action*

Even after Station 4 the external air should increase the pressure at the jet boundary. At high flight speeds this increase might be important. In a purely theoretical case it would imply the pressure distribution of a Laval nozzle. The expansion from Station 4 to Station 5 would be adiabatic-isentropic and $p_5=p_0$.

Then $$F_5=(Q_5/g)\,v_5>F_4$$

and $$F_{RE}=-F_3+F_5\gtreqless 0\,.$$

#### 1.4.2.3. *Probable external air inter-action*

The difference between $F_5$ and $F_4$ for normal pressure ratios is very small.

For turbo-jet engines where $0.2<v_0/v_4<0.5$ the influence of the external air flow is rather weak and it is suggested that $F_4$ is taken as representing the *exit thrust*, more usually called the *gross thrust*. Thus in this case, too, the rear external thrust is

$$F_{RE}=-F_3+F_4\,.$$

For rocket engines, where it is possible to have $v_0/v_4>1$ and still have positive forward thrust, $F_5$ could be greater than $F_4$.

### 1.4.3. *Supersonic aircraft*

With supersonic aircraft conical shocks may appear at the exit. Reasoning similar to that of Section 1.4.2 would apply in this case.

## 1.5. Total thrust

From the foregoing the total thrust of the jet engine is defined as

$$F=F_{FE}+F_I+F_{RE}\,,$$

which can be written

$$F=-F_0+F_4\,.$$

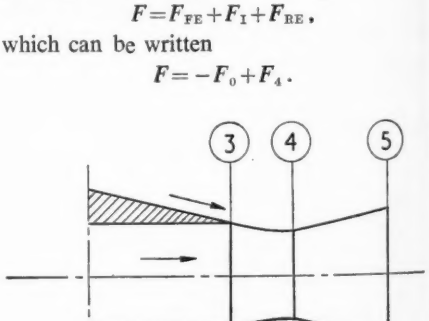



Fig. 5.

Here $F_0$ is the ram drag and $F_4$ is the gross thrust, which is now defined at the minimum section $A_4$ of the jet. This section can coincide with the exit, Station 3, but is often behind the engine.

The speed ratio $v_0/v_4$ increases with increasing aircraft speed and in many cases might imply a decrease of $A_4$. After the actual nozzle, ending at $A_3$, the engine has an "air nozzle" ending at $A_4$. Thus, the engine with a fixed nozzle area may have, in effect, a variable exit area.

When the engine thrust is defined in this way the aerodynamicist will have to define the aeroplane drag in a similar way.

The simple results quoted are valid if the engine air is drawn from the fresh atmosphere. If it is drawn, wholly or partly, from the boundary layer air a similar reasoning applies. A good treatment of this problem is given by Quick[6].

From what has been said previously it follows that the total thrust does not act on the engine mountings. There is little value, therefore, in measuring the force on the mountings.

An idling engine at high flight speed (*e.g.* during a deceleration) entails a high front external thrust. In one case a total thrust of 46 lb. was made up of a positive front external thrust of 330 lb. and a negative internal thrust of 284 lb. This rather high external thrust meant a considerable aerodynamic loading on the intake.

## 2. MEASUREMENT OF STATIC THRUST

### 2.1. General

The static thrust is not of great interest to the aeroplane designer as it is only one factor of the engine performance and is never used in flight. Different engines may have the same static thrust but give quite different altitude performance due, for example, to pressure ratio, turbine temperature and component efficiencies. However static thrust is useful as a guide to development work on a particular engine. The ratio fuel consumption/thrust (specific fuel consumption) is a significant figure and is related to the total efficiency of the engine. The thrust in static tests is measured in altitude plants (Section 3.3) and also in open test beds for calculating the altitude thrust as shown in Section 3.4. As this thrust is of great importance, it is obvious that it should be determined with maximum accuracy.

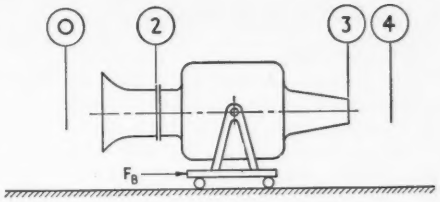



Fig. 6.

### 2.2. Engine with short integral intake pipe

The simplest installation for static tests has a short integral intake pipe as in Fig. 6. The force on the balance $F_B$ is the thrust $F_4$. If, however, the installation is such that the engine air has a small approach velocity in front of the engine, a ram drag is introduced which is difficult to determine. This error may amount to one per cent. of the thrust.

The thrust $F_4$ is valid for an installation characterised by the intake pressure drop $(p_4 - p_2''')$, $p_4$ being the atmospheric pressure behind the engine. This installed thrust $F_4$ can be converted to a *nominal thrust* $F_n$ valid at $p_4 = p_2'''$ in accordance with the methods of Section 4.1. For a subsonic exit pressure ratio the exit area of the engine working under nominal conditions will be smaller than the actual nozzle area.

### 2.3. Engine with long separate intake pipe

To achieve very accurate static thrust values it is advisable to use a long separate intake pipe as in Fig. 7. In altitude plants (Section 3.3) such an intake pipe is essential.

The joint between the intake pipe and the engine pipe can be described as a double-sided leather diaphragm. On this diaphragm there is a force $F_d$ acting which is approximately equal to $0.5A_d\ (p_{19} - p_{18}'')$. This force can be kept small by making the annular diaphragm area $A_d$ sufficiently small.

The forces satisfy the equation

$$F_4 = F_B + F_{18} - F_d\,,$$

with

$$F_{18} = (Q_{18}/g)\,v_{18} + A_{18}\,(p_{18}'' - p_4)\,.$$

The thrust $F_4$ refers to an intake pressure drop of $(p_4 - p_2''')$ and can be made a nominal thrust as mentioned in Section 2.2. The intake pipe can be calibrated to give $Q_{18}$ from the pressures $p_{17}'''$ and $p_{18}''$. The engine intake can be calibrated to give $p_2'''$ from $p_2''$ and $Q_{18}$.

## 3. THRUST IN FLIGHT

### 3.1. General

The thrust of the jet engine in flight enables the designer to estimate the aeroplane performance; but it must be the performance of the actual installation, with the actual intake flow and intake losses and the actual jet contraction. It is also necessary to know the aeroplane drag with the actual internal air flow since drag is a certain function of the internal flow. On the other hand the accuracy needed for the thrust is probably of the order of $\pm 2$ per cent. Therefore it is not advisable to spend time and money unnecessarily in obtaining still more accurate values. Moreover, a certain test engine may give different values of the thrust at different times because of variations in the condition of the engine components. In addition different engines of a production series will differ slightly in performance.

### 3.2. Measurement in flight

#### 3.2.1. *The jet pipe method*

Flight tests may be made in aircraft where the jet engine alone is responsible for flight, either in single-engined or multi-engined aircraft. Alternatively, the tests may be made in a flying test bed, often a four-engined bomber, where the aircraft is flown on other engines and the test engine is installed in the bomb bay or in the rear fuselage. The test methods are almost the same in all these cases.

The original method, used in most tests, is the "Jet Pipe Method." The gross thrust is calculated from a reading of the total pressure $p_3'''$ in the nozzle by the formula

$$F_4 = A_4\, p_0\, f_1(p_3'''/p_0)$$

where $A_4$ is assumed to be the exit area $A_3$. As a rule $p_3'''$ is read at only one pitot tube, being regarded as representative for the flow. The difference from the true mean value is small.

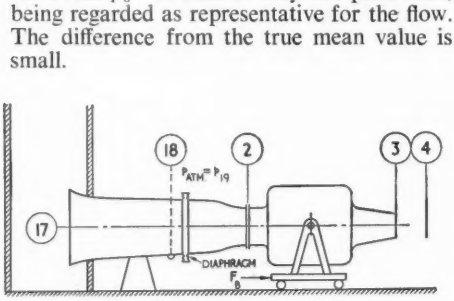



Fig. 7.

With the engine installed in the airframe the thrust is measured in a static test. From known values of $F_4$, $p_0$ and $p_3'''$ a "calibrated" value of $A_4$, often called the effective area, can be determined. The test gives

$$A_4 = f_2(p_3'''/p_0)\ .$$

This value of $A_4$ is then used to give the gross thrust in flight.

To determine the mass flow through the engine, which is necessary for the calculation of the ram drag, readings of thermocouples are taken in the exit. The temperatures recorded are supposed to give the temperatures with a certain recovery factor, *e.g.* 50 per cent., 85 per cent. or 98 per cent. Then the ram drag is obtained from the formula

$$F_0 = (v_0/g) f_3(T_3''', p_3'''/p_0, A_4)$$

The accuracy of the temperature measurement, $T_3'''$, seems to be rather questionable. The net or total thrust is

$$F = -F_0 + F_4\ .$$

This test method has a very weak point. If the area $A_4$ is variable at flight (in Section 1.4 it is assumed to decrease with increasing flight velocity) the calculated values of thrust will be wrong. Jet contraction to $A_4 < A_3$ gives a higher thrust than with $A_4 = A_3$. Since thrust is normally calculated with too large a value for $A_4$, both $F_4$ and $F_0$ will be too high and give a still higher net thrust $F$.

In one case, calculated from actual test figures, a true thrust increase of 3.5 per cent. due to jet contraction would, from the jet pipe reading, appear to be a 6.0 per cent. increase. The error is thus considerable and the test method may be regarded as being rather approximate.

There may also be a small variation in the area $A_3$ in flight due to temperature differences in the nozzle material.

#### 3.2.2. *Measurement with an exit rake*

To obtain better values than with the original single point in the jet pipe an instrument rake may be placed across the outlet area $A_3$. The rake has a number of total and static pressure tubes and thermocouples. From the readings, more accurate mean values of $p_3'''$, $p_3''$ and $T_3'''$ should be obtained. With a known value of $A_3$ the mass flow $Q_3$ can then be calculated. It is said, however, that it is difficult to get a rake which functions well. Vibrations have caused failure, and the static pressure measurement is often inaccurate. Therefore

it is suggested that the mass flow should be checked in the intake pipe.

Supposing that after tedious calculations, correct values for $p_3'''$, $p_3''$ and $T_3'''$ have been obtained from the test values, it is necessary to calculate the gross thrust $F_4$ by the method of Section 1. The gases have to be expanded to $A_4$ where, at subsonic pressure ratio $p_3'''/p_0$, the pressure is $p_0$ and, at supersonic pressure ratio, the Mach number $M_4$ equals unity. Then $F_4$ and $A_4$, which gives the jet contraction, can be computed.

It must be noted that the rake gives a new exit configuration to the engine and thus may change slightly the performance of the power plant.

3.2.3. *Measurement of engine mounting force*

It has been proposed that strain gauges at the engine mountings could give the thrust in flight, but it has already been pointed out in Section 1.5 that the mounting force, as a rule, is the internal thrust $F_I$, which gives no indication of the total thrust. Therefore the aircraft stress office need not assume more than a certain fraction of the total thrust in the mountings. The engine maker can give the appropriate fractions.

3.2.4. *Acceleration and deceleration of the aircraft*

As the foregoing methods are not exhaustive, other tests have been made. One series of trials has been reported by Trevelyan and Blundell[8]. A single-engined Goblin-Vampire was accelerated at full engine r.p.m. from low to high speed and decelerated from high to low speed with engine idling. The curve of speed against time gave the instantaneous acceleration or deceleration, and this multiplied by the aircraft mass gave the force acting. This force was regarded as equal to the engine thrust minus the aeroplane drag. The idling thrust of the engine was very small and could be determined from jet pipe measurements. Thus the drag was determined in deceleration and inserted in the acceleration equations, giving engine thrust at full r.p.m.

Assuming that the piloting technique, which is not easy, and the test values are correct, there is one point which should be noted. Under idling conditions the quantity of engine air is considerably smaller than at full r.p.m. The velocity ratio $v_1/v_0$ is very low; in Case 1 of Table I in Ref. 8 it is only

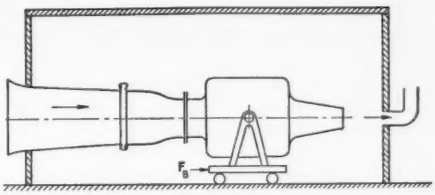



Fig. 8.

0.31. This low value may well give rise to additional drag, as described in Section 1.2. The figures quoted in Section 1.5, $F=46$ and $F_{FE}=330$, refer to this case. The high intake loading will tend to give too high a drag and hence values for the thrust which are also too high. It is obvious that the greater the aircraft speed, the greater the error. How large the errors may be, if they exist, it is impossible to conclude from Ref. 8.

With this fundamental weakness in the method it cannot be regarded as satisfactory for thrust measurement.

It may be noted that the methods described in Sections 3.2.1 and 3.2.4 tend to give too high values for the thrust and therefore also for the drag, which is not quite fair to the aircraft aerodynamicists.

3.3. MEASUREMENT IN ALTITUDE PLANTS

As already indicated, it is difficult to determine thrust accurately in flight tests. Furthermore it is not possible to test the engine outside the altitude and speed range of the test aircraft, and weather conditions put severe limitations on the number of flying hours a month. Therefore it has been suggested that jet engines should be tested in plants where the total pressure and temperature of the engine air corresponds to the atmospheric conditions at a certain height and aircraft speed. It is quite easy to provide the intake air, but it is more difficult and expensive to provide low pressure corresponding to high altitudes at the exit and to re-compress the low pressure exhaust gases to the ambient atmosphere. This is usually done by huge compressors and/or steam ejectors. The gases can be cooled in order to decrease the ejection work. Plants of this type have been built at Munich and in the United States of America.

The layout of such a plant is shown in Fig. 8. The intake air pipe is connected to the engine by a diaphragm. The test cell is held under the low simulated atmospheric pressure against which the engine exhausts.

In this installation the intake flow is not exactly simulated, but this is not important. It is more important that the external air flow at the exit should follow the actual aeroplane body at the appropriate flight speed and thereafter conform to the internal air flow. In the plant shown in Fig. 8 there is no representation of the aeroplane jet contraction, and the engine is not cooled at all. This limits the value of the estimated thrust. If an actual installation gives jet contraction in flight, the engine thrust is increased by an undetermined amount.

The foregoing conclusions agree with a statement by Hunsaker. It refers to supersonic aircraft, but should be true for subsonic conditions as well. Quoting Hunsaker from *Aero Digest*[1]:

"Air flow disturbances induced by the engine inlet or exhaust jet may seriously alter the effectiveness of the lifting and control surfaces of the airplane, whether the engine be located in a nacelle or totally submerged in the fuselage. Supersonic-propulsion systems no longer can be isolated for separated study but must be investigated with the complete aircraft configuration. . . . . To conduct this work, the engine nacelle must be submerged completely in a supersonic airstream, and reliable data can be obtained only with large-scale models. Especially valuable in this work is the Lewis Laboratory's 8 ft. by 6 ft. supersonic wind tunnel."

It might be added that in such tests it would be rather difficult to divide the measured force into engine thrust and nacelle drag, although this division would be unnecessary in many cases. In the Lewis tunnel there is probably no altitude simulation. Full-scale tests with such simulation would mean an extremely large and expensive plant. The correct use of such a plant as Fig. 8 represents, therefore, would be to confirm the satisfactory operation of the engine, especially with rapid changes of working conditions.

The most important factor during the development of a jet engine should be the testing of the components with exact simulation. Only after this is done should altitude tests with the whole engine be made. The absolute necessity of these latter tests is not immediately clear. Component testing and tests such as those of Section 3.5 should cover most problems.

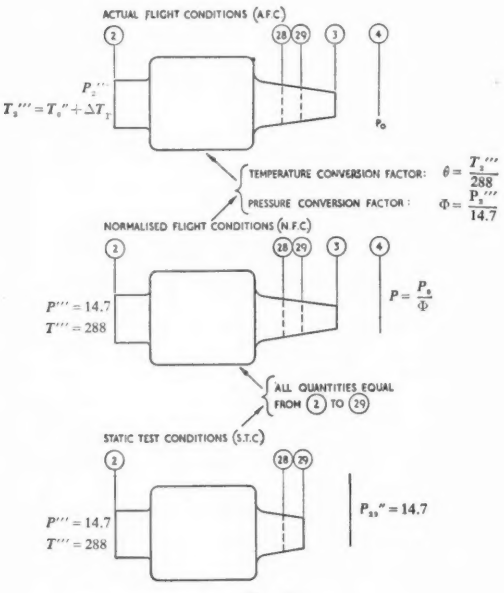



Fig. 9.

## 3.4. Static tests with jet diffusion

In Ref. 3 it is shown how the velocity of the engine jet can be used to maintain a lower pressure at the exit than at the intake of the engine. By this method parts of the flight thrust curves can be determined—provided that there is no jet contraction. The methods of calculation are given in Section 3.5.

The method used, however, seems to be technically unsound. To obtain an accurate thrust value is difficult because the rear, low pressure, part of the engine has to be sealed from the front part. This sealing will often give rise to parasitic forces. Moreover, as the jet exit is at atmospheric pressure, there is no purpose in expanding to low pressure and high velocity and then recompressing in long pipes. It is much simpler to test in ordinary static test-beds as shown in the following Section.

## 3.5. Static tests with different nozzle sizes

### 3.5.1. *Test procedure*

It is possible to simulate flight conditions by testing the jet engine in an ordinary static test bed if nozzles of different sizes are used. The test procedure, used earlier by the present author, has been demonstrated

recently by Sedille[7], but, as it seems to be both a useful and important method, a somewhat different approach is given here. The calculations are based on the normal laws of similarity, which are already accepted and used to obtain normalised test values, corresponding to 288°K. and 14.7 lb./in.$^2$

Figure 9 shows the principle. Under actual flight conditions (A.F.C.), there is a certain total pressure $p_2'''$ and total temperature $T_2'''$ at Station 2, and the engine works against the exit atmospheric pressure $p_0$. After the turbine there is somewhere a Station 29 where the static pressure $p_{29}''$ is equal to $p_2'''$. The Station 29 may well be situated behind the exit, as in the case of a static engine with intake pressure loss. The temperature $T_2'''$ is the atmospheric temperature $T_0''$ plus the ram temperature rise $\Delta T_r$. All quantities under A.F.C. can be converted, by the laws of similarity, to normalised flight conditions (N.F.C.) as shown in the centre diagram of Fig. 9. The conversion factors from N.F.C. to A.F.C. are $\theta = T_2'''/288$ for temperature and $\Phi = p_2'''/14.7$ for pressure.

The static test conditions (S.T.C.) corresponding to N.F.C. are shown at the bottom of Fig. 9. All quantities from Station 2 to the outlet are identically equal to the same quantities under N.F.C. The only difference is in the last part of the nozzle, which has a larger area (or a smaller area if Station 29 is situated behind the exit at A.F.C.) than under A.F.C. and N.F.C.

The most convenient criterion of similarity between A.F.C. and S.T.C. seems to be that the jet pipe temperature $T_{28}$ recorded under A.F.C. and converted to N.F.C. is identical with $T_{28}$ under S.T.C. It is important to notice that $T_{28}$ need not be a correct total or static temperature. It is essential only that the same instrument be used under A.F.C. and S.T.C. The temperature gauges can be the ordinary jet pipe gauges, which are standard equipment for jet engines. Usually four thermocouples are used.

The thrust $F$ under A.F.C. is calculated from $F_{NFC}$. The ram drag $F_0$ under N.F.C. is easily determined. The gross thrust under N.F.C. is computed from the gross thrust $F$ under S.T.C. Since the mass flow is the same under N.F.C. and S.T.C., only the change in exit velocity due to the residual pressure ratio need be considered. This is

$$14.7/(p_0/\Phi) = p_2'''/p_0 \gtrless 1 .$$

This pressure ratio is assumed to change the exit velocity isentropically-adiabatically. This assumption is justified by two facts. First the actual ratios are small as the true maximum Mach number equals unity. Secondly, tests with jet nozzles have shown that with increasing pressure ratio over the nozzle the entropy increase remains approximately constant.

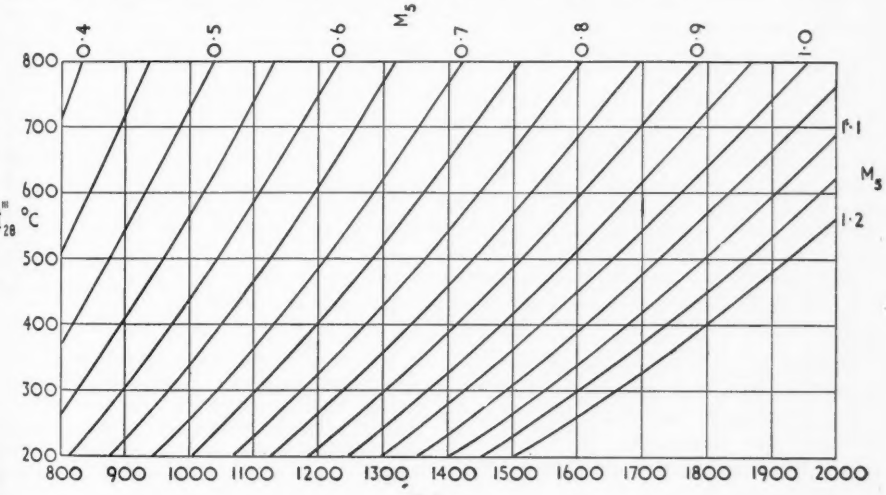



Fig. 10.

Theoretical adiabatic Mach number $M_5$ ($\gamma = 1.35$).

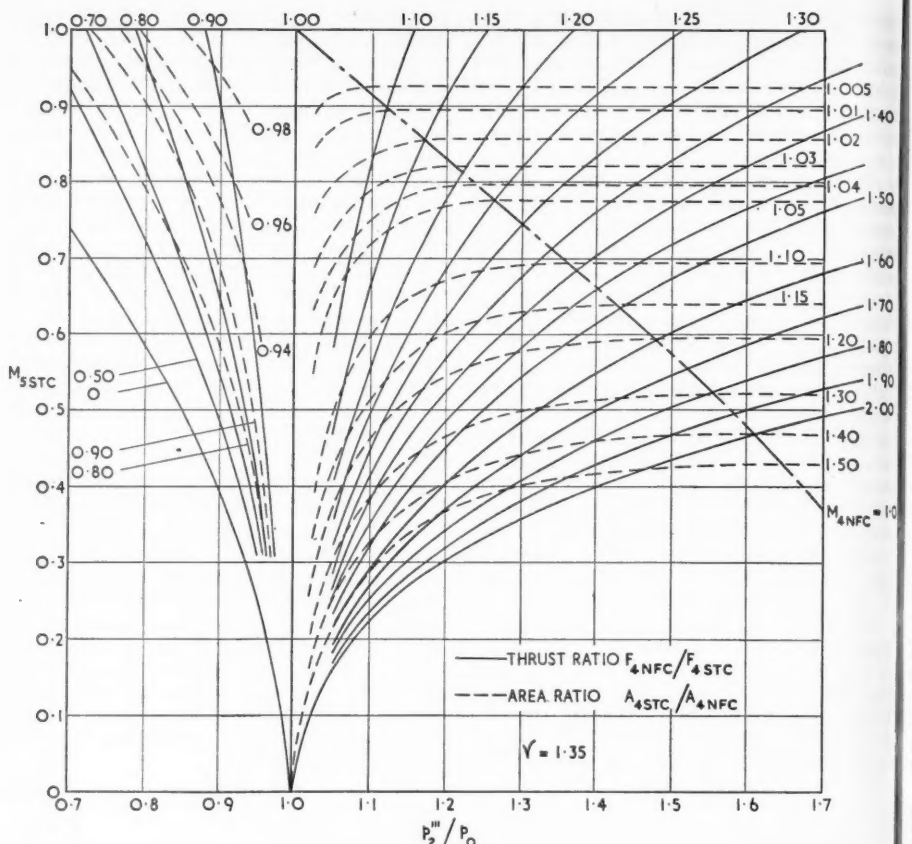



Fig. 11.

Under S.T.C. the effective exit velocity $v_4$ is calculated from the relation $v_4 = Fg/Q_4$ and the correct total temperature $T_{28}'''$ is measured. Using these values the theoretical adiabatic Mach number $M_5$ can be obtained from Fig. 10. Then the ratio $F_{4NFC}/F_{4STC} = f_3(p_2'''/p_0, M_5)$ is read from Fig. 11, together with the ratio $A_{4STC}/A_{4NFC}$. The area $A_{4STC}$, as a rule, should be the actual exit area under S.T.C.

Figures 10 and 11 are based on simple formulae which are not quoted here. A complete diagram, of which Fig. 11 is an enlarged part, is given in Fig. 18.

The formula for the thrust $F$ under A.F.C. is thus

$$F_{AFC} = \Phi\left[F_{STC} f_3(p_2'''/p_0, M_5) - \frac{Q_{4STC} v_0}{g\sqrt{\theta}}\right] \quad (7)$$

where $v_0$ is the actual flight speed and $v_0/\sqrt{\theta}$ is the normalised flight speed. The pressure $p_2'''$ can be calculated with different ram efficiencies or intake losses.

The formula for the fuel consumption $B_{AFC}$ is

$$B_{AFC} = \Phi\sqrt{\theta}\, B_{STC},$$

and for the specific fuel consumption $b_{AFC}$

$$b_{AFC} = B_{AFC}/F_{AFC}.$$

There are some questionable points in the suggested method. It is suspected that the area change from A.F.C. (=N.F.C.) to S.T.C., shown in Fig. 9 as a considerable shortening of the jet pipe, might change the losses and velocity distribution over the exit area. But the area changes are quite small and the different nozzles should be of constant length with only small differences in exit

diameter, say $\pm 5$ per cent. It may also be said that there is no simulation of the interaction between internal and external air flows. This is so, but the same is also true for the large altitude plants if they are not constructed as suggested in Ref. 1.

It is known that the combustion efficiency $\eta_b$ varies with the combustion chamber pressure. But this variation should be known from component tests with the chamber, making it possible to correct the "simulated consumption" to true consumption. No other corrections for this change in $\eta_b$ appear to be necessary.

The Reynolds numbers for A.F.C. at high altitude differ considerably from those at S.T.C. It is not possible to correct for this or to estimate its effect. Even at quite high altitude, however, the Reynolds number can be assumed to be sufficiently high to make the changes small. Tests can be made near the ground with small changes in Reynolds number.

The only way to determine the accuracy of the calculated $F_{\text{AFC}}$ is to make rigorous tests in an altitude plant as described in Section 3.3. These tests to check the validity of the laws of similarity ought to be done in the existing altitude plants, making additional plants unnecessary. Such tests are quoted by Driggs[2] and Figs. 24-27 of his paper show good agreement between tests and the theory of similarity.

From the foregoing it is clear that if altitude plants are to be used to determine flight thrust, it is desirable to test an engine with different nozzles and to quote the thrust as a function of $p_2'''$ and $T_{28}$. The measurement of these quantities in flight makes it possible to determine the accurate thrust under A.F.C.

### 3.5.2. *Comparison with Sedille's paper*

Comparing what has already been said with Sedille's treatment it is found that the basic theories are identical, but in this treatment the total pressure behind the turbine is omitted, since it is difficult to get an accurate mean value of this quantity. The jet pipe efficiency does not appear and the calculated thrust under A.F.C. is not based on a calculated nozzle area, since it is known that such calculations can give incorrect values. In this case thrust is calculated from the measured static thrust.

The area $A_{4\text{AFC}}$ $(=A_{4\text{NFC}})$ is calculated from $A_{4\text{STC}}$ and the area ratio read from Fig. 11. The variation of $A_{4\text{AFC}}$ with flight speed and altitude gives an indication of the jet contraction.

### 3.5.3. *Convenient form of static-test engine curves*

As the calculated flight thrust is based on $T_{28\text{STC}}$, it is convenient to give the static test results as functions of $T_{28}$ °K., or better $t_{28}$ °C., and the r.p.m. $n_{\text{STC}}=n_{\text{AFC}}/\sqrt{\theta}$. All the necessary data are found in the three diagrams of Fig. 12 applying to a particular engine. The symbols used are: $F_{\text{STC}}$ for percentage thrust, $Q_4$ for percentage mass flow, $B$ for percentage fuel consumption, $t_6$ for combustion chamber exit temperature, $M_5$ for adiabatic exit Mach number and $A_{4\text{STC}}$ for percentage exit area (here made equal to $A_3$).

It should be noted that all the quantities $F_{\text{STC}}$, $Q_4$, $M_5$, $t_{28}$ and $n_{\text{STC}}$ which are used in equation (7) to determine the thrust, are obtained in normal practice and are easy to measure accurately on a static test bed. If in the course of actual tests the thermocouples for $t_{28}$ should vary, they can be deduced from a number of static pressure readings (four, for example) taken at Station 28.

The flight thrust at different values of ram efficiency and jet contraction can be calculated from the curves of Fig. 12.

### 3.5.4. *Flight measurements required*

To get actual flight thrust from equation (7) and Fig. 12 it is necessary to determine in flight $n$, $t_{28}$, $T_2'''$ and the total and static pressure of the ambient air—which is already normal practice for jet aeroplanes—plus the total pressure $p_2'''$. This extra quantity is quite simply obtained. It can also be replaced by the static pressure $p_2''$ if curves for $p_2''$ are given in Fig. 12. (If boundary layer suction is used due allowance should be made.)

When the thrust has been determined, either from tests at constant speed or during an acceleration, by means of readings of air speed against time as in Ref. 8, the total drag coefficient $C_D$ can be calculated. The results can be given as $F=f_4(H,\ v_0,\ n)$, $C_D=f_5(H,\ v_0,\ n)$, and furthermore $A_{4\text{AFC}}=f_6(H,\ v_0,\ n)$.

### 3.5.5. *Possible range of flight data*

The pressure conversion factor $\Phi$ for $\eta_r=1$ at different values of $H$ and $v_0$ is shown

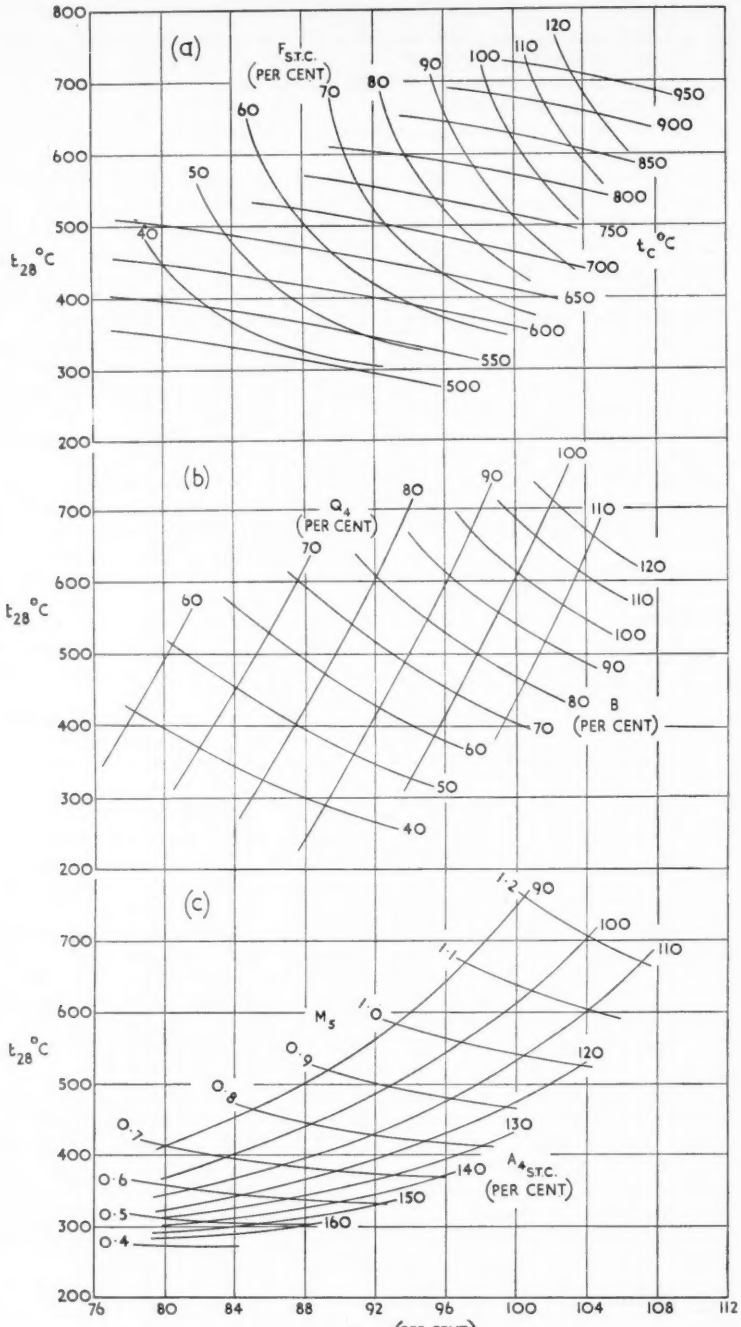

(a)
$F_{ST.C.}$ (PER CENT)
60
70
80
90
100
110
120
50
40
950
900
850
800
750
700
650
600
550
500
$t_c$ °C
$t_{28}$ °C
(b)
$Q_4$ (PER CENT)
60
70
80
90
100
110
120
50
40
B (PER CENT)
(c)
$M_5$
0·4
0·5
0·6
0·7
0·8
0·9
1·0
1·1
1·2
$A_{ST.C.}$ (PER CENT)
130
140
150
160
$\eta_{ST.C.}$ (PER CENT)
200
300
400
500
600
700
800
76
80
84
88
92
96
100
104
108
112

Fig. 12.

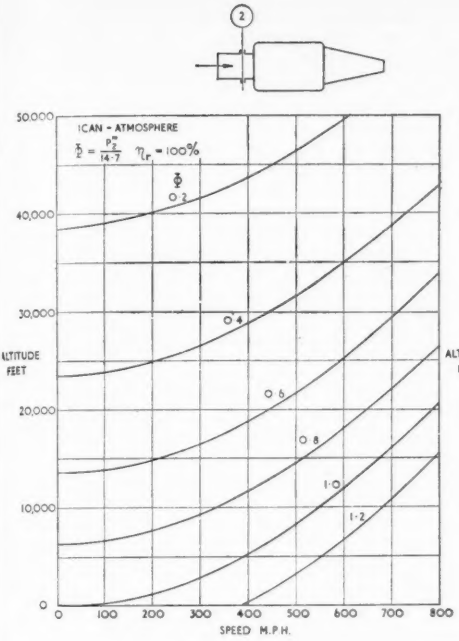



Fig. 13.

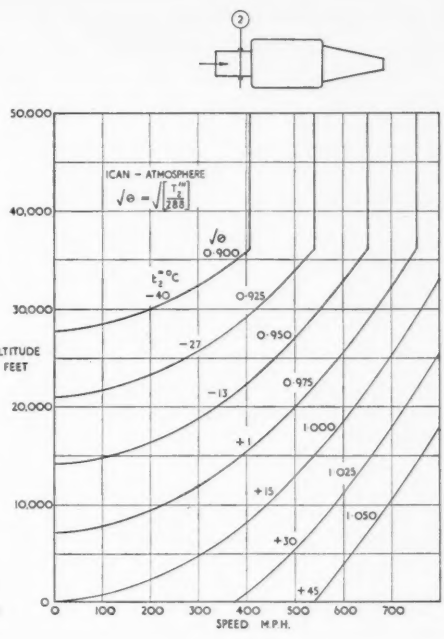



Fig. 14.

in Fig. 13. The variation of the square root of the temperature conversion factor ($\sqrt{\theta}$) is shown in Fig. 14. This graph shows the points that can be simulated in static tests and plotted in Fig. 12. At full r.p.m. the points to the right of the line for $t_2''' = 15°C.$ can be reached in static tests at $+15°C.$ in the atmosphere without over-speeding or over-heating the engine. The lower is the atmospheric temperature in the static tests the more to the left does the border line move. This shows clearly how useful are winter tests, *e.g.* in Canada or Alaska, for increasing the area covered in Fig. 14. At 90 per cent. r.p.m., however, points to the right of the line for $t_2''' = -40°C.$ can be tested at $+15°C.$ in the atmosphere as $n/\sqrt{\theta} = 90/0.90 = 100$ per cent. This means that static tests at 100 per cent. r.p.m. at $+15°C.$ correspond to 90 per cent. r.p.m. at $-40°C.$ Thus at 90 per cent. r.p.m. all the values of interest and at 100 per cent. r.p.m. many of the most interesting high speed values can be determined.

There is another limitation to the method. High speed flight at low r.p.m., say 60 per cent., involves static tests with quite large exit areas, say 150 per cent. The design of the exit, however, puts a limit to the convenient nozzle area. This is shown by Fig. 15. For a certain engine the maximum area was 25 per cent. larger than the normal, which meant that the 80 to 100 per cent. r.p.m. range could be fully tested. It is precisely these high r.p.m. values that are of practical importance and the limitation therefore is unimportant.

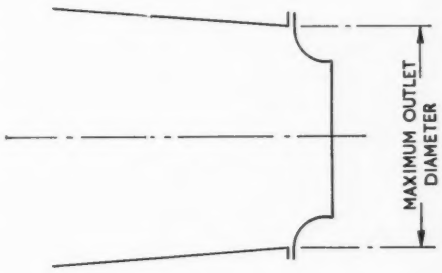



Fig. 15.

## 4. SOME SPECIAL PROBLEMS

### 4.1. THRUST WITH A PRESSURE LOSS IN THE ENGINE INTAKE PIPE

The engine working without loss in the intake pipe, *i.e.* at 100 per cent. ram efficiency, is said to give its *nominal thrust*, $F_n$. The problem is then to determine the thrust and the working conditions if there is an intake pressure loss of $\Delta p_2'''$.

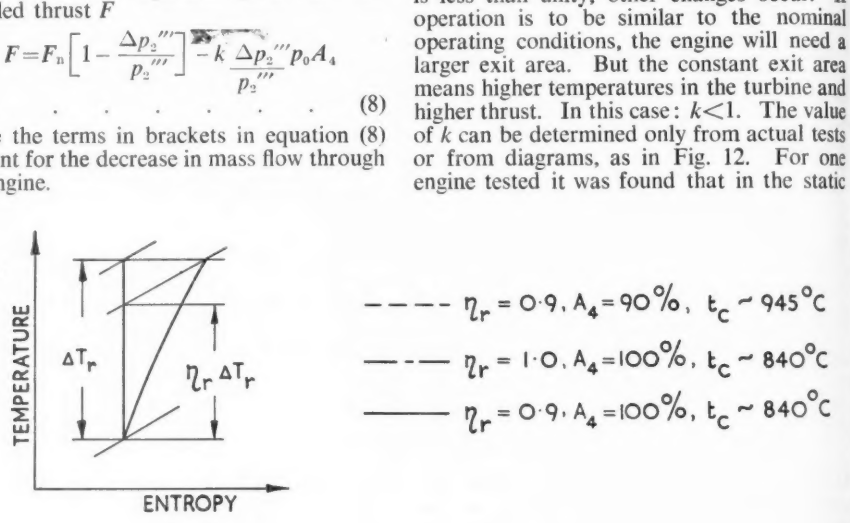
The following equation gives for the installed thrust $F$

$$F = F_n\left[1 - \frac{\Delta p_2'''}{p_2'''}\right] - k\,\frac{\Delta p_2'''}{p_2'''}\,p_0 A_4 \qquad (8)$$

where the terms in brackets in equation (8) account for the decrease in mass flow through the engine.

The second term in equation (8) is different in the following two cases. If the exit Mach number with intake loss is unity, the only change within the engine is the decrease in pressure and thus in mass flow. All temperatures and working points on the component characteristic lines are constant. In this case the factor $k$ in equation (8) is given by $k = 1$.

If the exit Mach number with intake loss is less than unity, other changes occur. If operation is to be similar to the nominal operating conditions, the engine will need a larger exit area. But the constant exit area means higher temperatures in the turbine and higher thrust. In this case: $k < 1$. The value of $k$ can be determined only from actual tests or from diagrams, as in Fig. 12. For one engine tested it was found that in the static



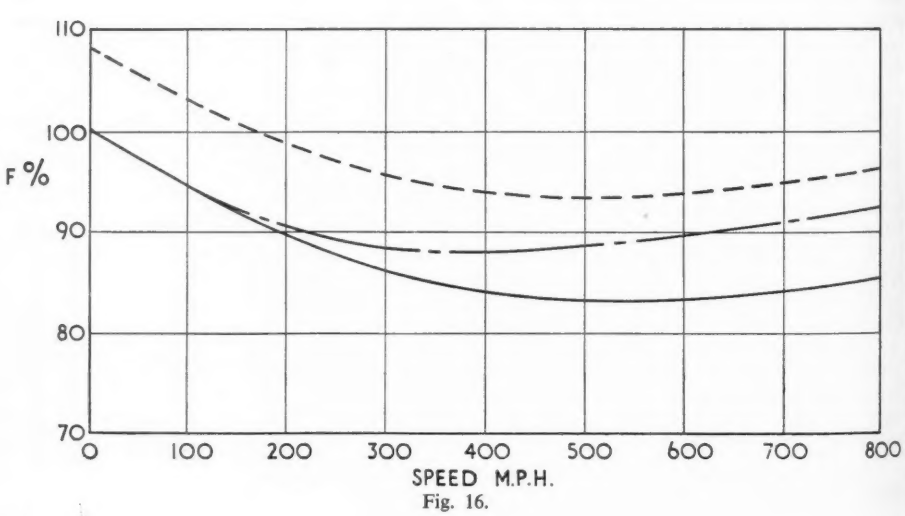




Fig. 16.

test $k=0.62$. The factor $k$ varies with altitude, flight speed and engine r.p.m. For most calculations it will be sufficient to use $k=1$.

### 4.2. Thrust increase due to jet contraction

The jet engine with jet contraction has considerably higher thrust than the engine without contraction. Thus a ram loss can be more than outweighed by the contraction. This is shown in one example in Fig. 16, which gives percentage thrust at different speeds at sea level and at full engine r.p.m. The curve for 100 per cent. ram efficiency and 100 per cent. $A_4$ can be compared with the curves for 90 per cent. ram efficiency with 100 per cent. and 90 per cent. $A_4$.

If this engine at 600 m.p.h. gives 90 per cent. thrust, this could be interpreted as 100 per cent. ram efficiency (at $t_c=840°$C.), thus indicating a high installed efficiency due to an efficient intake. But from Fig. 16 it appears that it could also be interpreted as a moderate (90 per cent.) ram efficiency and with a jet contraction of 94 per cent. $A_4$ (at $t_c=905°$C.). A dangerous factor is the much higher turbine temperature with jet contraction and the lower intake efficiency.

If this value of 90 per cent. thrust at 94 per cent. $A_4$ were determined by the jet pipe method, the tests would show approximately 96 per cent. thrust according to Section 3.2.1. Alternatively this result, without contraction, could be interpreted as 109 per cent. ram efficiency!

### 4.3. Wind tunnel testing of jet aeroplanes

When testing jet aeroplane models in wind tunnels it is necessary to have an internal air stream simulating the engine air. The quantity of internal air has been varied, *i.e.* different ratios $v_1/v_0$ have been used to show its effect on aeroplane drag. When the jet contraction is considered, however, it will be necessary to study the effect of different ratios $v_4/v_0$ and to determine the amount of jet contraction. If the internal air passes through the model without being heated, the ratio $v_1/v_4$ is constant. With correct area size this velocity ratio for a cold air stream is about one, but in the engine with hot outlet gases it is about three. In Fig. 17 the axes show the ratios $v_1/v_0$ and $v_4/v_0$. In normal wind tunnel tests points on the line

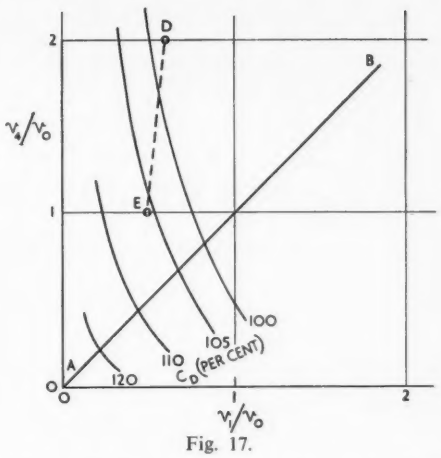


Fig. 17.

*AB* are obtained. But actual points in high speed flight from full engine r.p.m. to engine idling are found on the line *DE*. To simulate these conditions in a model air must be added to the internal flow.

If the drag $C_D$ is measured at different points, it is possible to determine the "iso-$C_D$-lines" shown in Fig. 17. In calculating the drag it is necessary to determine the thrust of the inside air and add this to the balance force.

## CONCLUSIONS

The paper, which suggests a basis for determining the thrust of jet engines, has been written from a purely theoretical point of view, and it will be of interest to see how the theory agrees with actual flight tests.

The test methods described will give accurate static thrust and suggest economical methods of determining flight thrust. They will also enable altitude plants to be used with better efficiency.

The jet contraction effect is thought to be a particularly important phenomenon.

The author feels that he may have been too critical of existing test methods and not critical enough of his own ideas. Therefore criticism will be valued and is awaited with interest.

It is hoped that the paper will give rise to discussion which will be of benefit to the technical development of jet engines.

## ACKNOWLEDGMENT

The author wishes to acknowledge his indebtedness to C. I. Dalhammar, of Svenska

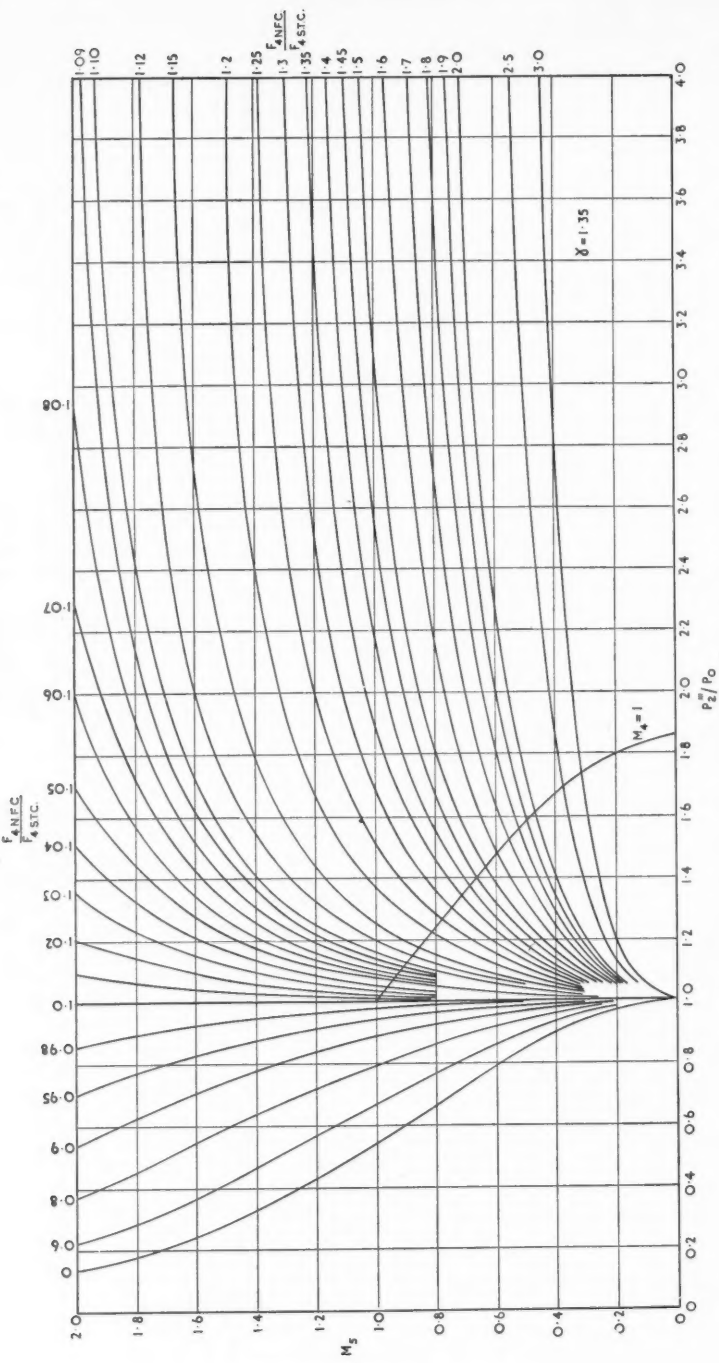



Fig. 18.
The thrust ratio $F_{4NFC}/F_{4STC}$ ($M_4$ is here $M_{4NFC}$ and $M_5$ is $M_{5STC}$).

Flygmotor A.B. (Swedish Aero Engine Co.) and O. Holme, of Flygtekniska Försöksanstalten (The Aeronautical Research Institute of Sweden) for valuable suggestions given during numerous discussions, and to thank Kungl. Flygförvaltningen (The Royal Air Board) and Svenska Flygmotor A.B. for permission to publish this paper.

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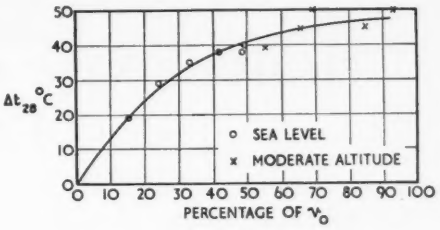


Fig. A1.

## APPENDIX

### TESTS SHOWING JET CONTRACTION

The following two tests are examples of jet contraction.

*(i) Wind tunnel*

In a test with $v_4 \simeq v_0$ the area ratio $A_4/A_3 = 0{\cdot}64$ (*See* Fig. 4) was obtained, which is a considerable contraction.

*(ii) Flight tests*

In a jet fighter the temperature $t_{28}$ increased from the value that should be obtained at constant exit area. The temperature increase ($\Delta t_{28}$) is shown in Fig. A1 as a function of percentage aeroplane velocity. This increase seems to be best interpreted as a jet contraction.

(Correspondence on this paper is invited—*Editor*)

THE ROYAL AERONAUTICAL SOCIETY

WITH WHICH IS INCORPORATED THE INSTITUTION OF AERONAUTICAL ENGINEERS

# EIGHTY-SIXTH ANNUAL REPORT OF THE COUNCIL 1950–1951

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## ANNUAL GENERAL MEETING

The Annual General Meeting of the Society, held on Monday, 15th May 1950, was reported in the Journal for December 1950.

## CHARTER OF INCORPORATION

The Charter of Incorporation of The Royal Aeronautical Society with which is incorporated the Institution of Aeronautical Engineers was granted by Letters Patent of His Majesty the King on 17th January 1949 and amended on 3rd February 1950, together with the By-Laws of the Society as allowed by the Lords of His Majesty's Most Honourable Privy Council on 30th January 1950.

The Charter and By-Laws were printed and circulated to all members with the October 1950 Journal.

## AERIAL SCIENCE LTD.

Under Clause 17 of the Charter of Incorporation of the Royal Aeronautical Society "The Society shall as soon as may be procure that Aerial Science Ltd. be wound up and that its surplus assets be transferred *in specie* to the Society . . . "

Under this Clause Aerial Science was liquidated in May 1950 and so, after close on forty years there came to an end the Limited Company which was legally responsible for the affairs of the Aeronautical Society of Great Britain and the Royal Aeronautical Society. The Directors of the Company could only be appointed by the Council of the Society, so ensuring the control of the Company by the Council.

The formation of Aerial Science Ltd. in 1911 enabled the Society to do many things which would have been difficult if not impossible while it remained a body as originally formed in 1866, for Aerial Science Ltd. made the Society a legal entity.

## MEMBERSHIP

There was a small increase in the total membership for the year 1950 over 1949. The effect of the new By-Laws raising the qualifications for election to Associate Fellowship and Associateship is beginning to show itself. The Council

feel confident that with the increasing complexities of aeronautics, it is only by so raising the technical qualifications for becoming an Associate Fellow and Associate, that the Society will maintain the high prestige which it now enjoys.

The Table gives the state of the membership at 31st December 1950. (*See* next page.)

## DIVISIONS

The Council are glad to record that the Australian, New Zealand and Southern Africa Divisions have all increased their membership during the year. The growth of these Divisions is one which will be of increasing importance in the development of Aeronautics in the Dominions overseas. These Divisions are autonomous with the exception that all applications for membership of the Society must pass through the London Headquarters, in order that a common standard of qualifications for election will be maintained.

## ASSOCIATE FELLOWSHIP EXAMINATION

During the year the revised syllabus for the Associate Fellowship Examination came into full operation, the first papers for Part II being set in May 1950. Candidates who had not completed the examination under the old regulations were able to sit the papers for the last time in August 1950.

With the introduction of the revised syllabus, the Society has raised the standard of its qualifications to a level in keeping with its prestige and standing.

## FELLOWSHIP

At the Annual General Meeting of the Society held on May 15th 1950 the following were elected Fellows of the Society:—

J. L. P. Brodie, M.I.A.E., M.I.Mech.E.
Air Vice-Marshal R. O. Jones, C.B., A.F.C.
E. J. Richards, M.A., B.Sc.
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F. W. Whitehead, M.I.Mech.E., M.I.P.E.
C. T. Wilkins

## LECTURES

During the year 14 Main lectures were held before the Society of which two were held at the following Branches:—

Manchester Branch—27th April 1950
Belfast Branch—7th November 1950

The year saw the first full year of the holding of the Section Lectures which were started in October 1949 to enable highly specialised aspects of aeronautical engineering and science to be discussed. These Section Lectures have proved successful even beyond the high hopes with which they were founded and they are now established as part of the regular programme of the Society's lectures.

A full list of lectures was published in the Journal for December 1950.

## WILBUR WRIGHT MEMORIAL LECTURE

The 38th Wilbur Wright Memorial Lecture was read on Thursday 25th May 1950 by Sir Richard Fairey on "Some Aspects of Expenditure on Aviation." The complete report was published in the July 1950 Journal.

## BRITISH COMMONWEALTH AND EMPIRE LECTURE

The Sixth British Commonwealth and Empire Lecture was read on Thursday 28th September 1950 by Sir George Cribbett on "Some International Aspects of Air Transport with Particular Reference to Future Aircraft Operation." The complete report was published in the November 1950 Journal.

## MEMBERSHIP

The following table shows the state of the Membership:—

### MEMBERSHIP AT 31st DECEMBER 1950

| Grade | London Register | Australian Division | New Zealand Division | Southern Africa Division | Life and Honorary | Totals | Suspended Members (included in foregoing figures) |
|---|---|---|---|---|---|---|---|
| Fellows ... | 350 (353) | 12 (10) | 1 (2) | 1 (1) | 47 (44) | 411 (410) | 2 (5) |
| Associate Fellows | 2611 (2498) | 71 (63) | 30 (28) | 42 (41) | 12 (10) | 2766 (2640) | 89 (62) |
| Associates ... | 1994 (2064) | 71 (64) | 51 (45) | 91 (85) | 4 (4) | 2211 (2262) | 164 (186) |
| Graduates ... | 1177 (1110) | 31 (17) | 5 (3) | 2 (2) | — (—) | 1215 (1132) | 37 (28) |
| Students ... | 761 (860) | 53 (46) | — (—) | 2 (3) | — (—) | 816 (909) | 84 (97) |
| Founder Members | 16 (17) | — (—) | — (—) | — (—) | 1 (1) | 17 (18) | 2 (2) |
| Companions | 167 (189) | 2 (2) | 1 (2) | 5 (3) | 11 (6) | 186 (202) | 18 (14) |
| Temporary Hon. Members | — (—) | — (—) | — (—) | — (—) | 41 (37) | 41 (37) | — (—) |
| | 7076 (7091) | 240 (202) | 88 (80) | 143 (135) | 116 (102) | 7663 (7610) | 396 (394) |

Figures in brackets are corresponding figures at 31st December 1949

## LOUIS BLERIOT LECTURE

The Third Louis Bleriot Lecture was read in Paris on Thursday 4th May 1950 by Sir Frederick Handley Page on "Towards Slower and Safer Flying, Improved Take-Off and Landing and Cheaper Airports." A complete report was published in the December 1950 Journal.

## BRANCHES

133 Lectures were read before the Branches during the year, of which two were Main Lectures.

During 1950 the Council approved the formation of two more Branches of the Society at Halton and Chester. This brings the total number of Branches in Great Britain and Northern Ireland up to twenty-one. During the year all Branches were active and the standard of lectures read before them was extremely high. The total number of non-Society members of Branches is approximately four thousand.

All the Branches of the Society combined to assist at the Annual Garden Party in May 1950. A comprehensive model display was staged in the hangar and demonstrations of control line flying were included in the flying programme. This is the first time that the Branches of the Society have taken any major part in a main Society function of this nature, and it is hoped as opportunities occur to obtain the assistance of the Branches in other activities of the Society.

The Society continue to hold two of the main lectures outside London, the Branches in turn acting as hosts to the Society. These lectures have proved to be extremely successful and the attendance compares favourably with the lectures read in London.

During the year the President has visited the majority of the Branches and it is expected that by the completion of his term of office in May 1951 he will have been present at a meeting of each of the Branches in this country.

## ELECTION OF PRESIDENT AND VICE-PRESIDENTS

Major G. P. Bulman, C.B.E., F.R.Ae.S., was elected President of the Society for the year 1950-51 at the Council Meeting on 31st March 1950 and took office at the Annual General Meeting on 15th May 1950.

The following were elected Vice-Presidents of the Society for the year 1950-51 at the Meeting of Council held on 24th May 1950:—

S. Camm, C.B.E., F.R.Ae.S.
G. R. Edwards, M.B.E., B.Sc., F.R.Ae.S.
Major F. B. Halford, C.B.E., F.R.Ae.S.

## GRADUATES' AND STUDENTS' SECTION

During the year the Graduates' and Students' Section held nine meetings. The lectures read before the Section at these meetings proved very successful. During the year the Section published in their special Journal leaflet a series of papers which were written by their Honorary Secretary, M. C. Campion.

In September 1949 there was appointed for the first time a Graduates' and Students' Commitee of Council. This Committee consists of nine members, three elected by the Council and six elected by the Graduates and Students of the Society. The names of the Committee are given in the list of Committees at the beginning of this Report.

## FINANCE

The Income and Expenditure Accounts and Balance Sheets of the Royal Aeronautical Society and Aeronautical Trusts Ltd. for 1950 are published with this Report.

## Balance Sheet

| 1949 Figures | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| £ | s. | d. | | | £ | s. | d. | | £ | s. | d. |
| | | | *Current Liabilities*— | | | | | | | | |
| 5161 | 15 | 11 | Sundry Creditors ... ... ... ... ... | | 4838 | 3 | 11 | | | | |
| 452 | 17 | 3 | Amount due to Aeronautical Trusts Ltd., Royal Aeronautical Society Endowment Fund ... | | — | — | — | | | | |
| 2225 | 6 | 0 | Subscriptions and other amounts received in advance ... ... ... ... ... ... | | 1901 | 2 | 8 | | 6739 | 6 | 7 |
| 7839 | 19 | 2 | | | | | | | | | |
| | | | *Surplus*— | | | | | | | | |
| | | | *Publications Development Account*— | | | | | | | | |
| | | | Balance at 31st December 1949 ... ... ... | | 4797 | 13 | 4 | | | | |
| | | | *Deduct*—Expenditure on AERONAUTICAL QUARTERLY, *less* sales, during year ... ... | | 933 | 7 | 3 | | | | |
| 4797 | 13 | 4 | | | 3864 | 6 | 1 | | | | |
| | | | *Reserve for Anglo-American Conference 1951*— | | | | | | | | |
| — | — | — | Transfer from Income and Expenditure Account | | 1250 | 0 | 0 | | | | |
| | | | *Income and Expenditure Account*— | | | | | | | | |
| | | | Balance at 31st December 1949 ... | 4523 13 4 | | | | | | | |
| | | | *Add*—Surplus of Income over | | | | | | | | |
| 4523 | 13 | 4 | Expenditure for year to date ... | 477 8 5 | 5001 | 1 | 9 | | 10115 | 7 | 10 |
| 9321 | 6 | 8 | | | | | | | | | |
| £17161 | 5 | 10 | | | | | | | £16854 | 14 | 5 |

G. P. BULMAN, *President.*

C. F. UWINS, *Honorary Treasurer.*

REPORT OF THE AUDITORS TO THE MEMBERS

In our opinion and to the best of our information and according to the explanations given to us, the above Aeronautical Society Endowment Fund included in the annexed accounts of Aeronautical Trusts Ltd., give a true and accounts are in agreement therewith.

We have obtained all the information and explanations which to the best of our knowledge and belief were

3 Frederick's Place, Old Jewry, London, E.C.2.
*8th March* 1951.

## Income and Expenditure Account

| 1949 Figures | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| £ | s. | d. | | | £ | s. | d. | | £ | s. | d. |
| | | | To Establishment Expenses— | | | | | | | | |
| 2472 | 3 | 3 | Ground Rent, Heating, Lighting, Insurance and Repairs ... ... ... ... ... | | | | | | 1882 | 7 | 5 |
| | | | „ Office and Staff Expenses— | | | | | | | | |
| 6895 | 18 | 4 | Salaries ... ... ... ... ... ... | | 7327 | 11 | 2 | | | | |
| 295 | 4 | 7 | Staff Pension Premiums ... ... ... | | 328 | 8 | 5 | | | | |
| 1545 | 7 | 11 | Printing and Stationery ... ... ... | | 1536 | 6 | 6 | | | | |
| 1267 | 2 | 9 | Postages and Telephones ... ... ... | | 1151 | 17 | 3 | | | | |
| 111 | 15 | 0 | Office Equipment ... ... ... ... | | — | — | — | | | | |
| 1141 | 16 | 3 | Other Charges ... ... ... ... ... | | 638 | 14 | 7 | | 10982 | 17 | 11 |
| 11257 | 4 | 10 | | | | | | | | | |
| | | | „ JOURNAL and Sundry Publications— | | | | | | | | |
| 16134 | 10 | 9 | Printing Costs ... ... ... ... ... | | 13972 | 2 | 6 | | | | |
| 1713 | 10 | 8 | Postages ... ... ... ... ... ... | | 1856 | 6 | 6 | | | | |
| 1986 | 11 | 8 | Other Charges ... ... ... ... ... | | 1907 | 2 | 0 | | | | |
| 19834 | 13 | 1 | | | 17735 | 11 | 0 | | | | |
| 4266 | 16 | 7 | *Less*—Sales ... ... ... | 4193 7 6 | | | | | | | |
| 8614 | 0 | 0 | Advertisement Revenue ... | 9649 10 0 | 13842 | 17 | 6 | | 3892 | 13 | 6 |
| 6953 | 16 | 6 | | | | | | | | | |
| | | | „ Expenditure on Data Sheets—*Less* amounts | | | | | | | | |
| 3754 | 4 | 10 | recoverable ... ... ... ... ... | | | | | | 117 | 9 | 2 |
| 431 | 17 | 8 | „ Meetings ... ... ... ... ... ... | | | | | | 495 | 11 | 8 |
| 2032 | 8 | 5 | „ Reserve for Anglo-American Conference 1951 ... | | | | | | 1250 | 0 | 0 |
| (1949 Conference) | | | | | | | | | | | |
| 117 | 12 | 11 | „ Garden Party ... ... ... ... ... | | | | | | 490 | 14 | 1 |
| 410 | 11 | 11 | „ Dinners and Receptions ... ... ... | | | | | | 469 | 14 | 2 |
| 971 | 17 | 8 | „ Library Expenses ... ... ... ... | | | | | | 1294 | 7 | 11 |
| 308 | 6 | 6 | „ Branch Expenses ... ... ... ... | | | | | | 326 | 12 | 6 |
| 90 | 15 | 7 | „ Prizes and Donations ... ... ... | | | | | | 164 | 9 | 2 |
| 100 | 0 | 0 | „ Charter Scholarship ... ... ... | | | | | | 300 | 0 | 0 |
| 368 | 2 | 0 | „ Legal and Professional Charges ... ... | | | | | | 895 | 6 | 10 |
| 466 | 15 | 9 | „ Cost of Charter ... ... ... ... | | | | | | — | — | — |
| — | — | — | „ Balance, being Surplus of Income over Expenditure for year, carried to Balance Sheet ... | | | | | | 477 | 8 | 5 |
| £29735 | 17 | 10 | | | | | | | £23039 | 12 | 9 |

# AERONAUTICAL SOCIETY

BY ROYAL CHARTER 1949)

## 31st December 1950

| 1949 Figures £ s. d. | | £ s. d. | £ s. d. |
|---|---|---|---|
| | *Current Assets—* | | |
| 7801 4 2 | Investments at cost ... ... ... ... ... (Market Value 31st December 1950, £7841) | 7801 4 2 | |
| 1 0 0 | Stock of Journals and other publications ... | 1 0 0 | |
| 4295 10 10 | Sundry Debtors ... ... ... ... ... | 4236 3 10 | |
| 219 1 1 | Payments in Advance ... ... ... ... | 338 18 11 | |
| 4793 8 9 | Cash at Bank and in Hand ... ... ... | 3797 5 6 | 16174 12 5 |
| 17110 4 10 | | | |
| | *Aeronautical Trusts Ltd.—* | | |
| 1 1 0 | 21 Shares of 1s. each fully paid at cost ... ... | 1 1 0 | |
| — — — | Amount due on Current Account ... ... ... | 629 1 0 | 630 2 0 |
| | *Printed Books, Bindings, Old Prints, etc.—* | | |
| 50 0 0 | At nominal amount ... ... ... ... | | 50 0 0 |
| £17161 5 10 | | | £16854 14 5 |

OF THE ROYAL AERONAUTICAL SOCIETY

balance sheet and the annexed income and expenditure account of the Society together with the accounts of the Royal fair view of the state of the Society's affairs as at 31st December 1950 and of its surplus for the year ended on that date. necessary for our audit. In our opinion the Society has kept proper books of account and the above mentioned

(*Signed*) PRICE, WATERHOUSE & CO.

## for the Year ended 31st December 1950

| 1949 Figures £ s. d. | | £ s. d. | £ s. d. |
|---|---|---|---|
| 21326 1 2 | By Annual Subscriptions ... ... ... ... | | 21670 3 3 |
| 428 9 6 | „ Donations ... ... ... ... ... ... | | 745 10 6 |
| 89 3 9 (Gross) | „ Interest on Investments (*less* Tax) ... ... | 124 10 4 | |
| 75 9 2 (*Less* Tax) | | | |
| — — — | „ Income Tax Recovered ... ... ... ... | 135 7 6 | |
| 2982 15 5 | „ Interest on Endowment Fund Investments (*less* expenses) ... ... ... ... ... ... | — — — | 259 17 10 |
| 3147 8 4 | | | |
| | „ Examinations— | | |
| 1200 4 0 | Fees received ... ... ... ... ... | 894 6 0 | |
| 926 6 7 | *Less*—Expenses ... ... ... ... ... | 530 4 10 | 364 1 2 |
| 273 17 5 | | | |
| 4560 1 5 (Excess of Expenditure over Income) | | | |
| £29735 17 10 | | | £23039 12 9 |

## Balance Sheet

| 1949 Figures | | | | £ s. d. | £ s. d. | £ s. d. |
|---|---|---|---|---|---|---|
| | | | *Share Capital—* | | | |
| | | | *Authorised*—40 shares of 1s. each .. .. .. .. | | 2 0 0 | |
| 1 | 1 | 0 | *Issued*—21 shares of 1s. each fully paid .. .. .. | | | 1 1 0 |
| | | | *Royal Aeronautical Society Endowment Fund—* | | | |
| 130699 | 13 | 5 | *Capital Account*—Balance at 31st December 1949 .. | | 131954 8 5 | |
| 11 | 11 | 0 | *Add*—Donations received during year .. .. .. | | 1 1 0 | |
| 1243 | 4 | 0 | Entrance Fees received during year .. .. | | 927 0 0 | |
| 131954 | 8 | 5 | | | 132882 9 5 | |
| — | — | — | *Less*—Loss on Realisation of Investments .. .. | | 1232 17 4 | |
| | | | | | 131649 12 1 | |
| 5799 | 17 | 3 | *Income Account*—Balance at 31st December 1949 .. | 5799 17 3 | | |
| — | — | — | *Add*—Surplus of Income over Expenditure for year to date | 3303 17 3 | 9103 14 6 | 140753 6 7 |
| 137754 | 5 | 8 | | | | |
| | | | *Pilcher Memorial Fund—* | | | |
| 99 | 14 | 0 | *Capital Account*—As at 31st December 1949 .. .. | | 99 14 0 | |
| 68 | 19 | 8 | *Income Account*—Balance as at 31st December 1949 .. | 74 7 0 | | |
| 5 | 7 | 4 | *Add*—Surplus of Income over Expenditure for year to date | 2 4 | 74 9 4 | 174 3 4 |
| 174 | 1 | 0 | | | | |
| | | | *Usborne Memorial Fund—* | | | |
| 109 | 2 | 5 | *Capital Account*—As at 31st December 1949 .. .. | | 109 2 5 | |
| 80 | 13 | 4 | *Income Account*—Balance at 31st December 1949 .. | 81 12 8 | | |
| 19 | 4 | | *Add*—Surplus of Income over Expenditure for year to date | 14 4 | 82 7 0 | 191 9 5 |
| 190 | 15 | 1 | | | | |
| | | | *Herbert Akroyd Stuart Fund—* | | | |
| 691 | 9 | 0 | *Capital Account*—As at 31st December 1949 .. .. | | 691 9 0 | |
| 527 | 8 | 7 | *Income Account*—Balance at 31st December 1949 .. | 544 0 5 | | |
| 16 | 11 | 10 | *Add*—Income for year to date .. .. .. .. | 37 11 10 | 581 12 3 | 1273 1 3 |
| 1235 | 9 | 5 | | | | |
| | | | *R.38 Memorial Fund—* | | | |
| 981 | 13 | 10 | *Capital Account*—As at 31st December 1949 .. .. | | 981 13 10 | |
| 810 | 2 | 10 | *Income Account*—Balance at 31st December 1949 .. | 869 2 0 | | |
| 58 | 19 | 2 | *Add*—Income for year to date .. .. .. .. | 58 19 2 | 928 1 2 | 1909 15 0 |
| 1850 | 15 | 10 | | | | |
| | | | *Edward Busk Memorial Fund—* | | | |
| 449 | 6 | 1 | *Capital Account*—As at 31st December 1949 .. .. | | 449 6 1 | |
| 223 | 4 | 11 | *Income Account*—Balance at 31st December 1949 .. | 222 17 3 | | |
| 7 | 8 | | *Add*—Surplus of Income over Expenditure for year to date | 3 10 4 | 226 7 7 | 675 13 8 |
| (Deficit) | | | | | | |
| 672 | 5 | 4 | | | | |
| | | | *Wilbur Wright Memorial Fund—* | | | |
| 2136 | 17 | 11 | *Capital Account*—As at 31st December 1949 .. .. | | 2136 17 11 | |
| 207 | 14 | 2 | *Income Account*—Balance at 31st December 1949 .. | 213 12 6 | | |
| 5 | 18 | 4 | *Add*—Surplus of Income over Expenditure for year to date | 5 18 4 | 219 10 10 | 2356 8 9 |
| 2350 | 10 | 5 | | | | |
| | | | *Simms Gold Medal Fund—* | | | |
| 527 | 15 | 9 | *Capital Account*—As at 31st December 1949 .. .. | | 527 15 9 | |
| 48 | 2 | 11 | *Income Account*—Balance at 31st December 1949 .. | 64 10 3 | | |
| 16 | 7 | 4 | *Add*—Surplus of Income over Expenditure for year to date | 15 8 | 65 5 11 | 593 1 8 |
| 592 | 6 | 0 | | | | |
| | | | *Alston Memorial Fund—* | | | |
| 245 | 6 | 0 | *Capital Account*—As at 31st December 1949 .. .. | | 245 6 0 | |
| 65 | 14 | 5 | *Income Account*—Balance at 31st December 1949 .. | 69 12 7 | | |
| 3 | 18 | 2 | *Add*—Surplus of Income over Expenditure for year to date | 3 18 2 | 73 10 9 | 318 16 9 |
| 314 | 18 | 7 | | | | |
| | | | *Geoffrey de Havilland Memorial Fund—* | | | |
| 4175 | 17 | 5 | *Capital Account*—As at 31st December 1949 .. .. | | 4175 17 5 | |
| 66 | 14 | 6 | *Income Account*—Balance at 31st December 1949 .. | 133 9 0 | | |
| 66 | 14 | 6 | *Add*—Surplus of Income over Expenditure for year to date | 108 12 0 | 242 1 0 | 4417 18 5 |
| 4309 | 6 | 5 | | | | |
| £149445 | 12 | 9 | | | | £152664 15 10 |

G. P. BULMAN, *President.*
C. F. UWINS, *Honorary Treasurer.*

REPORT OF THE AUDITORS TO THE

In our opinion and to the best of our information and according to the explanations given to us the above Company's affairs and of the Funds administered by it as at 31st December 1950 and of the surplus of the Funds
We have obtained all the information and explanations which to the best of our knowledge and belief were accounts, which are in agreement therewith, give in the prescribed manner the information required by the Companies
3 Frederick's Place, Old Jewry, London, E.C.2.
8*th March* 1951.

# TRUSTS LIMITED

## 31st December 1950

| 1949 Figures | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| £ | s. | d. | | | | | | | £ | s. | d. | £ | s. | d. | £ | s. | d. |
| 1 | 1 | 0 | *Cash in Hand* .. .. .. .. .. .. .. | | | | | | | | | | | | 1 | 1 | 0 |
| | | | *Royal Aeronautical Society Endowment Fund—* | | | | | | | | | | | | | | |
| | | | Leasehold Property at cost—*Less* amounts written off 4, 8 and 9 Hamilton Place at cost— | | | | | | | | | | | | | | |
| 12120 | 16 | 6 | Balance at 31st December 1949 .. .. .. | | | | | | 12120 | 16 | 6 | | | | | | |
| — | — | — | *Add*—Expenditure during year .. .. .. | | | | | | 2064 | 5 | 3 | | | | | | |
| | | | | | | | | | 14185 | 1 | 9 | | | | | | |
| 5330 | 16 | 6 | *Less*—Amortisation written off to date .. .. | | | | | | 5816 | 1 | 9 | 8369 | 0 | 0 | | | |
| 6790 | 0 | 0 | Furniture at cost—*Less* depreciation— | | | | | | | | | | | | | | |
| 4570 | 5 | 0 | At cost .. .. .. .. .. .. | | | | | | 4570 | 5 | 0 | | | | | | |
| 2259 | 5 | 0 | *Less*—Depreciation written off to date .. .. | | | | | | 2487 | 15 | 0 | 2082 | 10 | 0 | | | |
| 2311 | 0 | 0 | | | | | | | | | | | | | | | |
| 127942 | 16 | 9 | Investments at cost .. .. .. .. .. .. | | | | | | | | | 119731 | 6 | 1 | | | |
| | | | (Market Value 31st December 1950, £113,949, including £1,000 2½% Defence Bonds (unquoted) at cost.) | | | | | | | | | 130182 | 16 | 1 | | | |
| | | | Current assets— | | | | | | | | | | | | | | |
| — | — | — | Sundry debtors .. .. .. .. .. .. | | | | | | 375 | 0 | 0 | | | | | | |
| 257 | 11 | 8 | Cash at Bank .. .. .. .. .. .. | | | | | | 10824 | 11 | 6 | 11199 | 11 | 6 | | | |
| | | | | | | | | | | | | 141382 | 7 | 7 | | | |
| 452 | 17 | 3 | *Less*—Amount due to Royal Aeronautical Society .. | | | | | | | | | 629 | 1 | 0 | 140753 | 6 | 7 |
| (Amount due from Royal Aeronautical Society) | | | | | | | | | | | | | | | | | |
| 137754 | 5 | 8 | | | | | | | | | | | | | | | |
| | | | *Pilcher Memorial Fund—* | | | | | | | | | | | | | | |
| 156 | 5 | 0 | Investment at cost .. .. .. .. .. .. .. .. | | | | | | | | | 156 | 5 | 0 | | | |
| | | | (Market Value 31st December 1950, £145) | | | | | | | | | | | | | | |
| 17 | 16 | 0 | Cash at Bank .. .. .. .. .. .. .. .. | | | | | | | | | 17 | 18 | 4 | 174 | 3 | 4 |
| 174 | 1 | 0 | | | | | | | | | | | | | | | |
| | | | *Usborne Memorial Fund—* | | | | | | | | | | | | | | |
| 174 | 11 | 1 | Investment at cost .. .. .. .. .. .. .. .. | | | | | | | | | 174 | 11 | 1 | | | |
| | | | (Market Value 31st December 1950, £161) | | | | | | | | | | | | | | |
| 16 | 4 | 0 | Cash at Bank .. .. .. .. .. .. .. .. | | | | | | | | | 16 | 18 | 4 | 191 | 9 | 5 |
| 190 | 15 | 1 | | | | | | | | | | | | | | | |
| | | | *Herbert Akroyd Stuart Fund—* | | | | | | | | | | | | | | |
| 1102 | 15 | 8 | Investment at cost .. .. .. .. .. .. .. .. | | | | | | | | | 1102 | 15 | 8 | | | |
| | | | (Market Value 31st December 1950, £1,012) | | | | | | | | | | | | | | |
| 132 | 13 | 9 | Cash at Bank .. .. .. .. .. .. .. .. | | | | | | | | | 170 | 5 | 7 | 1273 | 1 | 3 |
| 1235 | 9 | 5 | | | | | | | | | | | | | | | |
| | | | *R.38 Memorial Fund—* | | | | | | | | | | | | | | |
| 1754 | 6 | 2 | Investment at cost .. .. .. .. .. .. .. .. | | | | | | | | | 1754 | 6 | 2 | | | |
| | | | (Market Value 31st December 1950, £1,588) | | | | | | | | | | | | | | |
| 96 | 9 | 8 | Cash at Bank .. .. .. .. .. .. .. .. | | | | | | | | | 155 | 8 | 10 | 1909 | 15 | 0 |
| 1850 | 15 | 10 | | | | | | | | | | | | | | | |
| | | | *Edward Busk Memorial Fund—* | | | | | | | | | | | | | | |
| 658 | 8 | 8 | Investments at cost .. .. .. .. .. .. .. .. | | | | | | | | | 658 | 8 | 8 | | | |
| | | | (Market Value 31st December 1950, £691) | | | | | | | | | | | | | | |
| 13 | 14 | 8 | Cash at Bank .. .. .. .. .. .. .. .. | | | | | | | | | 17 | 5 | 0 | 675 | 13 | 8 |
| 672 | 3 | 4 | | | | | | | | | | | | | | | |
| | | | *Wilbur Wright Memorial Fund—* | | | | | | | | | | | | | | |
| 2250 | 14 | 9 | Investments at cost .. .. .. .. .. .. .. .. | | | | | | | | | 2250 | 14 | 9 | | | |
| | | | (Market Value 31st December 1950, £2,405) | | | | | | | | | | | | | | |
| 99 | 15 | 8 | Cash at Bank .. .. .. .. .. .. .. .. | | | | | | | | | 105 | 14 | 0 | 2356 | 8 | 9 |
| 2350 | 10 | 5 | | | | | | | | | | | | | | | |
| | | | *Simms Gold Medal Fund—* | | | | | | | | | | | | | | |
| 504 | 12 | 0 | Investments at cost .. .. .. .. .. .. .. .. | | | | | | | | | 504 | 12 | 0 | | | |
| | | | (Market Value 31st December 1950, £476) | | | | | | | | | | | | | | |
| 87 | 14 | 0 | Cash at Bank .. .. .. .. .. .. .. .. | | | | | | | | | 88 | 9 | 8 | 593 | 1 | 8 |
| 592 | 6 | 0 | | | | | | | | | | | | | | | |
| | | | *Alston Memorial Fund—* | | | | | | | | | | | | | | |
| 290 | 0 | 0 | Investments at cost .. .. .. .. .. .. .. .. | | | | | | | | | 290 | 0 | 0 | | | |
| | | | (Market Value 31st December 1950, £299) | | | | | | | | | | | | | | |
| 24 | 18 | 7 | Cash at Bank .. .. .. .. .. .. .. .. | | | | | | | | | 28 | 16 | 9 | 318 | 16 | 9 |
| 314 | 18 | 7 | | | | | | | | | | | | | | | |
| | | | *Geoffrey de Havilland Memorial Fund—* | | | | | | | | | | | | | | |
| 4175 | 17 | 5 | Investment at cost .. .. .. .. .. .. .. .. | | | | | | | | | 4175 | 17 | 5 | | | |
| | | | (Market Value 31st December 1950, £3,923) | | | | | | | | | | | | | | |
| 133 | 9 | 0 | Cash at Bank .. .. .. .. .. .. .. .. | | | | | | | | | 242 | 1 | 0 | 4417 | 18 | 5 |
| 4309 | 6 | 5 | | | | | | | | | | | | | | | |
| £149445 | 12 | 9 | | | | | | | | | | | | | £152664 | 15 | 10 |

MEMBERS OF AERONAUTICAL TRUSTS LTD.

balance sheet and the annexed income and expenditure accounts give a true and fair view of the state of the for the year ended on that date.
necessary for our audit. In our opinion the company has kept proper books of account and the above mentioned Act, 1948.

(*Signed*) PRICE, WATERHOUSE & CO.

# AERONAUTICAL

## Income and Expenditure Accounts

## Royal Aeronautical Society

| 1949 Figures £ s. d. | | £ s. d. |
|---|---|---|
| 485 0 0 | To Amortisation of Leasehold Property ... ... ... ... | 485 5 3 |
| 228 11 9 | „ Depreciation of Furniture ... ... ... ... ... ... | 228 10 0 |
| — — — | „ Legal Expenses ... ... ... ... ... ... ... | 5 5 0 |
| 2982 15 5 | „ Surplus of Income over Expenditure for year carried to Balance Sheet ... ... ... ... ... ... ... ... | 3303 17 3 |
| £3696 7 2 | | £4022 17 6 |

**Pilcher**

| | | |
|---|---|---|
| — — — | To 1950 Award ... ... ... ... ... ... ... ... | 5 5 0 |
| 5 7 4 (Income) | „ Surplus of Income over Expenditure for year carried to Balance Sheet ... ... ... ... ... ... ... ... | 2 4 |
| £5 7 4 | | £5 7 4 |

**Usborne**

| | | |
|---|---|---|
| 5 0 0 | To 1950 Award ... ... ... ... ... ... ... ... | 5 5 0 |
| 19 4 | „ Surplus of Income over Expenditure for year carried to Balance Sheet ... ... ... ... ... ... ... ... | 14 4 |
| £5 19 4 | | £5 19 4 |

**Herbert Akroyd**

| | | |
|---|---|---|
| 21 0 0 (Award) | To Income for year carried to Balance Sheet ... ... ... | 37 11 10 |
| 16 11 10 (Surplus of Income) | | |
| £37 11 10 | | £37 11 10 |

**R.38**

| | | |
|---|---|---|
| 58 19 2 | To Income for year carried to Balance Sheet ... ... ... | 58 19 2 |
| £58 19 2 | | £58 19 2 |

**Edward Busk**

| | | |
|---|---|---|
| 21 0 0 | To 1950 Award ... ... ... ... ... ... ... ... | 21 0 0 |
| — — — | „ Surplus of Income over Expenditure for year carried to Balance Sheet ... ... ... ... ... ... ... ... | 3 10 4 |
| £21 0 0 | | £24 10 4 |

**Wilbur Wright**

| | | |
|---|---|---|
| 75 0 0 | To 1950 Award ... ... ... ... ... ... ... ... | 75 0 0 |
| 5 18 4 | „ Surplus of Income over Expenditure for year carried to Balance Sheet ... ... ... ... ... ... ... ... | 5 18 4 |
| £80 18 4 | | £80 18 4 |

**Simms Gold**

| | | |
|---|---|---|
| — — — | To 1950 Award ... ... ... ... ... ... ... ... | 15 11 8 |
| 16 7 4 (Income) | „ Surplus of Income over Expenditure for year carried to Balance Sheet ... ... ... ... ... ... ... ... | 15 8 |
| £16 7 4 | | £16 7 4 |

**Alston**

| | | |
|---|---|---|
| 5 0 0 | To 1950 Award ... ... ... ... ... ... ... ... | 5 0 0 |
| 3 18 2 | „ Surplus of Income over Expenditure for year carried to Balance Sheet ... ... ... ... ... ... ... ... | 3 18 2 |
| £8 18 2 | | £8 18 2 |

**Geoffrey de Havilland**

| | | |
|---|---|---|
| — — — | To 1950 Award ... ... ... ... ... ... ... ... | 40 0 0 |
| 66 14 6 (Income) | „ Surplus of Income over Expenditure for year carried to Balance Sheet ... ... ... ... ... ... ... ... | 108 12 0 |
| £66 14 6 | | £148 12 0 |

# TRUSTS LIMITED

## for the Year ended 31st December 1950

### Endowment Fund

| 1949 Figures £ s. d. | | £ s. d. |
|---|---|---|
| 3379 18 6 | By Interest on Investments (Gross) ... ... ... ... ... | 2642 1 4 |
| 316 8 8 | „ Interest on Investments (*less* Tax) ... ... ... ... ... | 477 7 8 |
| — — — | „ Refund of Income Tax ... ... ... ... ... | 206 6 9 |
| — — — | „ Interest on Deposit Account ... ... ... ... ... | 75 10 3 |
| — — — | „ Rents Receivable ... ... ... ... ... ... ... | 621 11 6 |
| £3696 7 2 | | £4022 17 6 |

### Memorial Fund

| | | |
|---|---|---|
| 5 7 4 | By Interest on Investments (Gross) ... ... ... ... ... | 5 7 4 |
| £5 7 4 | | £5 7 4 |

### Memorial Fund

| | | |
|---|---|---|
| 5 19 4 | By Interest on Investments (Gross) ... ... ... ... ... | 5 19 4 |
| £5 19 4 | | £5 19 4 |

### Stuart Fund

| | | |
|---|---|---|
| 37 11 10 | By Interest on Investments (Gross) ... ... ... ... ... | 37 11 10 |
| £37 11 10 | | £37 11 10 |

### Memorial Fund

| | | |
|---|---|---|
| 58 19 2 | By Interest on Investments (Gross) ... ... ... ... ... | 58 19 2 |
| £58 19 2 | | £58 19 2 |

### Memorial Fund

| | | |
|---|---|---|
| 15 17 0 | By Interest on Investments (Gross) ... ... ... ... ... | 15 17 0 |
| 4 15 4 | „ Interest on Investments (*less* Tax) ... ... ... ... ... | 4 15 4 |
| — — — | „ Refund of Income Tax ... ... ... ... ... | 3 18 0 |
| 7 8 | | |
| (Excess of Expenditure over Income) | | |
| £21 0 0 | | £24 10 4 |

### Memorial Fund

| | | |
|---|---|---|
| 80 18 4 | By Interest on Investments (Gross) ... ... ... ... ... | 80 18 4 |
| £80 18 4 | | £80 18 4 |

### Medal Fund

| | | |
|---|---|---|
| 16 7 4 | By Interest on Investments (Gross) ... ... ... ... ... | 16 7 4 |
| £16 7 4 | | £16 7 4 |

### Memorial Fund

| | | |
|---|---|---|
| 8 18 2 | By Interest on Investments (Gross) ... ... ... ... ... | 8 18 2 |
| £8 18 2 | | £8 18 2 |

### Memorial Fund

| | | |
|---|---|---|
| 66 14 6 | By Interest on Investments (*less* Tax) ... ... ... ... ... | 66 14 6 |
| — — — | „ Refund of Income Tax ... ... ... ... ... | 81 17 6 |
| £66 14 6 | | £148 12 0 |

## HONORARY FELLOWSHIP

The following were awarded Honorary Fellowship of the Society in 1950:—

Robert Blackburn, O.B.E., A.M.Inst.C.E., M.I.Mech.E., M.I.P.E.
Sir Richard Fairey, M.B.E.
T. O. M. Sopwith, C.B.E.
Lt.-Col. Mervyn O'Gorman, C.B., D.Sc., M.I.Mech.E., M.I.E.E.
Sir Francis K. McClean, A.F.C.

## HONORARY COMPANIONS

The following were appointed Honorary Companions of the Society in 1950:—

Marshal of the R.A.F. The Lord Douglas of Kirtleside, G.C.B., K.C.B., M.C., D.F.C.
Air Marshal Sir Alec Coryton, K.B.E., C.B., M.V.O., D.F.C.
Major Sir Hew Kilner, M.C.
C. G. Grey.

## HONOURS

The following members of the Society received awards in 1950:—

NEW YEAR HONOURS—JANUARY 1950

| | |
|---|---|
| K.B.E. | Air Vice-Marshal A. de T. Nevill, *Associate Fellow* (President, New Zealand Division of the Royal Aeronautical Society) |
| C.B. | S. Scott Hall, *Fellow* |
| | Air Commodore J. F. Titmas, *Associate Fellow* |
| C.B.E. | F. M. Owner, *Fellow* |
| | K. T. Spencer, *Fellow* |
| O.B.E. | R. M. Clarkson, *Fellow* |
| | W. Courtenay, *Associate* |
| | G. B. S. Errington, *Associate Fellow* |
| M.B.E. | J. Norman, *Associate Fellow* |
| KING'S COMMENDATION FOR VALUABLE SERVICES IN THE AIR | |
| | Air Vice-Marshal D. C. T. Bennett, *Fellow* |

BIRTHDAY HONOURS

| | |
|---|---|
| BARON | E. W. Hives, *Fellow* |
| G.C.B. | Air Chief Marshal Sir Ralph Cochrane, *Associate Fellow* |
| K.C.B. | Sir Ben Lockspeiser, *Fellow* |
| C.B.E. | F. T. Hearle, *Fellow* |
| | Captain J. Laurence Pritchard, *Hon. Fellow* |
| | T. Rowntree, *Fellow* |
| O.B.E. | H. P. Folland, *Fellow* |

## INSTITUTE OF THE AERONAUTICAL SCIENCES

The Council of the Institute announced the following elections of members of the Society in 1950:—

To *Fellowship*:

Dr. J. J. Green, F.R.Ae.S.
A. E. Russell, F.R.Ae.S.
Bo K. Lundberg, A.F.R.Ae.S.

## GUGGENHEIM MEDAL

The Guggenheim Medal (U.S.A.) for 1950 was awarded to Dr. E. P. Warner, *Honorary Fellow*. The medal is awarded for pioneering in research and a continuous record of contributions to the art and science of Aeronautics.

## THE ROYAL SOCIETY

The following members of the Society were made *Fellows* of the Royal Society in 1950:—

R. A. Fraser, B.A., D.Sc., *Fellow*,
S. B. Gates, O.B.E., *Fellow*,
L. Howarth, B.Sc., M.A., Ph.D., *Associate Fellow*.

The Rumford Medal of the Royal Society was awarded to Air Commodore Sir Frank Whittle, K.B.E., C.B., D.Sc., F.R.S., F.R.Ae.S.

## OFFICERS AND COMMITTEES

The Council wish to place on record their appreciation of the work which has been done by the Honorary Officers of the Society during the year.

C. F. Uwins, the Honorary Treasurer, has given invaluable advice and help in financial matters.

J. E. Hodgson, Honorary Librarian for so many years, has again during the year 1950 continued to advise the Society on all matters pertaining to the Library.

The Council wish to place on record the work of their various committees. It is upon the papers and reports from these committees that the Council acts and they particularly wish to record the work done by the Finance Committee, the Grading Committee and the Examinations Committee, which have done so much to safeguard the membership and finances of the Society.

## MEDALS AND AWARDS

The following medals and awards were presented at the Thirty-Eighth Wilbur Wright Memorial Lecture on 25th May 1950:—

*The Society's Gold Medal*
Sir Geoffrey de Havilland, for his outstanding work in the field of aviation.

*The Society's Silver Medal*
J. Smith, for his outstanding work on the design and development of high performance R.A.F. and Naval aircraft.
W. E. W. Petter, for his outstanding work on high performance aircraft—especially the Canberra (the award to Mr. Petter was made at the British Commonwealth and Empire Lecture on 28th September).

*The Society's Bronze Medal*
A. C. Lovesey, for his outstanding contribution to engine development.

*British Gold Medal for Aeronautics*
Major F. B. Halford, for his outstanding work in the design and development of aircraft power plants.

*British Silver Medal for Aeronautics*
Group Captain P. W. S. Bulman and Captain J. Summers, for their long and distinguished work in the flight testing of aircraft.

*George Taylor (of Australia) Gold Medal*
E. J. Richards, for his paper on A Review of Aerodynamic Cleanness.

*Simms' Gold Medal*
Dr. D. E. Adams and Dr. A. N. Uttley, for their paper on Navigational Systems and Instrument Aids.

*Edward Busk Memorial Prize*
D. L. Ellis, for his paper on Industrial Wind Tunnels.

*Pilcher Memorial Prize*
J. Hahn, for his paper on Training of Aeronautical Engineers.

*Usborne Prize*
C. M. Britland, for his paper on Helicopter Hovering Performance.

*Orville Wright Prize*

G. W. Trevelyan and D. R. Blundell, for their paper on Determination of the Drag of Jet-Propelled Aircraft in Flight.

*Branch Prize*

Wing Commander E. A. Harrop, for his paper on Planned Servicing in the R.A.F., read before the Brough Branch.

*R. P. Alston Memorial Prize*

P. Goodman, for his valuable and careful work as a Flight Observer.

## BADEN POWELL MEMORIAL PRIZE

The Baden Powell Memorial Prize was awarded to B. E. Boyce, who was considered by the Society's Examiners to be the best student in the December 1949 Associate Fellowship Examination.

## ELLIOTT MEMORIAL PRIZE

The Elliott Memorial Prize was awarded to 583943 Armitage, M. J., F.II.A.—Corporal, the Aircraft Apprentice of the May 1947 Entry who obtained the highest marks in the General Studies Examination; to 584266 Murray, A. R., F.II.A.—Sergeant Aircraft Apprentice, the Aircraft Apprentice of the September 1947 Entry who obtained the highest marks in the General Studies Examination; and to 584592 Boyle, D., F.II.A.—Leading Aircraft Apprentice, the Aircraft Apprentice of the January 1948 Entry who obtained the highest marks in the General Studies Examination.

## JOURNAL PREMIUM AWARDS

The following Premium Awards were made in 1950 for papers published in the Journal during 1949:—

H. S. Crabtree, for his paper on Airlines Engineering Service Experience and its use in the Design of Aircraft, Fifteen Guineas, February 1949 Journal.

J. H. Argyris and P. C. Dunne, for their papers on The General Theory of Cylindrical and Conical Tubes under Torsion and Bending Loads, Fifteen Guineas, May and June 1949 Journals.

F. W. Page and J. C. King, for their papers on Structural Test Frame with Automatic Loading, Fifteen Guineas, October 1949 Journal.

L. W. Rosenthal, for his paper on Weight of Seaplane Floats, Fifteen Guineas, September 1949 Journal.

C. M. Britland, for his paper on Helicopter Hovering Performance.

## ROYAL AERONAUTICAL SOCIETY CHARTER SCHOLARSHIP

The Charter Scholarship for 1950-51 was awarded to John Anthony Dunsby, B.Sc., D.I.C., *Graduate.*

## THE GEOFFREY DE HAVILLAND MEMORIAL SCHOLARSHIP

The Geoffrey de Havilland Memorial Scholarship for the year 1950-1951 was awarded to Denys John Mead, *Graduate.*

## GARDEN PARTY

The Society's Annual Garden Party was held on Sunday 14th May 1950, and a full account was published in the July 1950 Journal.

## ACKNOWLEDGMENTS

Items presented to the Society during the year were acknowledged in the Journal for December 1950.

## DONATIONS

The Council wish to place on record their grateful thanks to the Society of British Aircraft Constructors, the Ministry of Supply, the British Overseas Airways Corporation, Sir George Nelson and Sir Frederick Handley Page, for their generous donations to the funds of the Society, donations which have enabled the Council to press forward with the aims and objects of the Society.

## APPOINTMENT OF SECRETARY

Following consideration of upwards of 250 applications for the post of Secretary, Dr. A. M. Ballantyne, B.Sc., A.F.R.Ae.S., has been appointed by the Council and will take up his duties on 2nd July 1951. The Council invited Captain J. Laurence Pritchard, C.B.E., Hon.F.R.Ae.S., to continue in the service of the Society until the completion of the Anglo-American Conference in September 1951, a task he has accepted and he has personally undertaken all the organisation in collaboration with the Institute of the Aeronautical Sciences which he visited for the purpose in January 1951. The Institute of the Aeronautical Sciences will thus have the opportunity to share with the members of the Society in paying tribute to the unique services rendered by Captain Pritchard over so many years, on his retirement.

## STAFF

The President and Council wish to record their grateful thanks to all the staff for their unremitting, conscientious, and most loyal services throughout the year, upon which, under the direction of the Secretary, the continuing success and efficient administration of the Society's business are wholly dependent.

# REVIEW

JET AIRCRAFT POWER SYSTEMS. Jack V. Casamassa. McGraw-Hill Book Co., New York. 1950. 338 pp. Illustrated. Appendix. Index. 47s. net.

One reads this book with mixed impression. Some of it is good; some not so good. Perhaps this could be expected since the book admits to being a condensate of available information on jet propulsion and it is only natural that the editor reflects something of the quality of the papers or publications from which he has prepared his distillate.

The author is the Director of the Engine Department of the Academy of Aeronautics, La Guardia, New York, and his objective is to introduce the principles of turbine power plants to students and users of turbine-powered aircraft. As such an introduction, the book serves a useful purpose; as a text book for technical institutes, it can be regarded at best as a supplement.

Although the book is based on experiences with American engines, the introductory chapter contains a generous reference to the work of Power Jets and Sir Frank Whittle culminating in the despatch of the first jet unit to America in October 1941. As a result, the first American jet aircraft (Bell XP.59) flew in 1942 and the long and successful line of Lockheed P-80 "Shooting Stars" was set off by another British engine in 1944.

In addition to describing turbo-jets and turbo-props., the book has sections on ram-jets, pulse jets and rockets. On these latter subjects, the information available is, of necessity, restricted. Incidentally, a turbo-prop. is defined as an axial-flow gas turbine equipped with reduction gears and propeller. The author seems unaware of the centrifugal compressors of the Dart, which engined the first aircraft with turbine-driven propellers to operate on a regular airline service. This is just one example of an annoying lack of care that crops up here and there in the text when dealing with basic facts and principles.

Sections describing power plant components are followed by chapters dealing with thrust augmentation, materials, fuel systems, lubrication systems, ignition and starting. Often these systems are described in quite unnecessary detail when their defects are so apparent and their standard only transient. Some interesting facts on the reliability of American engines and on improvements arising from development are given in a chapter on service experience mainly derived from papers read before the Society of Automotive Engineers and the Institute of the Aeronautical Sciences.

A good feature of the book is a list of references at the end of each chapter and a series of questions which are well posed to ensure that the student has read carefully the preceding section. Unfortunately many of these questions are a test of memory rather than a test of the knowledge of the principles expounded.

A section deals with the compounding of piston engines with gas turbines, based mainly on the work of Wright Aeronautical and Pratt & Whitney in this field. Finally, there is a chapter on jet transports (which term also includes propeller-turbine installations) where very proper reference is made to the Comet, the Jetliner and the Viscount.

The book concludes with addenda on some of the latest developments and with a glossary on "Jet Lingo" which is an illuminating and amusing introduction to pilots' slang in this jet age.

# CORRESPONDENCE

## SENSITIVITY OF WIRE RESISTANCE STRAIN GAUGES

In his paper, "Modern Methods of Testing Aero-engines and Power Plants" (June 1950 JOURNAL, A. C. Lovesey), I was surprised to see Mr. Lovesey's statement (p. 350) that, other things being equal, the sensitivity of wire resistance strain gauges varies directly as their resistivity. I gather from the remainder of the text that he meant "resistance" rather than "resistivity."

Surely, this dependance of sensitivity on resistance is quite incorrect, although it is a fallacy which is far too frequently encountered. Sensitivity depends solely on the material from which the wire is made, and on the manner in which the gauge is wound insofar as this affects the proportion of the total length of wire in the gauge which is actually subjected to strain. The following figures for nickel chrome gauges, which are taken from Dobie and Isaacs' book, "Electric Resistance Strain Gauges," will illustrate my point:—

| Gauge Manufacturer | Nominal Resistance (ohms) | Length (inch) | Sensitivity |
|---|---|---|---|
| Rotol | 200 | 0.5 | 1.5 |
| „ | 10,000 | 0.6 | 1.7 |
| de Havilland | 2,400 | 1.75 | 2.2 |
| „ | 8,000 | 1.75 | 2.2 |

It will be seen that the sensitivity varies between 1.5 and 2.2, there being very little increase in sensitivity as the gauge resistance is increased from 200 to 10,000 ohms.

The great advantage of the high resistance strain gauge when measuring strains in moving parts is its large absolute change in resistance for a given strain. If this absolute change can be made sufficiently large as compared with changes in resistance which occur at brushes and slip rings while running, it can reduce considerably the effect which these unwanted changes have on the accuracy of the observed results; but it has no advantage where sensitivity is concerned.

**S. B. Bailey,** *Associate Fellow*

Mr. Bailey is quite correct. The paper would have been correct if the passage in question had read: "other things being equal the usable sensitivity of wire resistance strain gauges used through mercury type slip rings varies directly as their resistance."

The point is that we are limited in the current that we can pass through the slip-rings for a given background "mush" and the voltage of the signal that is obtained for a given strain is proportional to the strain gauge resistance. As Mr. Bailey points out it is misleading to refer to this voltage for a given stress as the sensitivity, a term which is defined as the proportional change in resistance for unit strain.

**A. C. Lovesey,** *Fellow*

## TIME REQUIRED FOR LEVEL SPEED MEASUREMENT

Mr. Lush is to be thanked for his paper "A Note on the Time Required to Make a Level Speed Measurement with a Turbine-Jet Aircraft" (October 1950 JOURNAL). He should be congratulated for bringing to notice an interesting aspect of modern aeroplane behaviour. He attacks the problem in a most elegant mathematical fashion, but I must admit that when I read his paper through I was left with a vague unsatisfied feeling—it was only after several patient re-readings that I traced my disquiet to his factor $Y$. He states that variations in this are responsible for about half the total magnitude of the effect under consideration on jet aircraft. Apparently, the values of $Y$ have to be read off from curves which were not presented.

As one whose predominant interest is in engines, I feel that more information on this side would help to complete the picture. Accordingly, I have tried to deduce succinctly the variations in $Y$ from fundamental relations for gas turbines.

The following symbols and subscripts are employed. To avoid confusion with temperatures, Mr. Lush's $T$ for thrust has been converted to $X$ in the present notation. $T$ stands for temperature, $P$ for pressure (lb./in.$^2$), $A$ for air mass flow (lb./sec.), $V$ for aircraft speed in ft./sec., $N$ for engine r.p.m., $v$ for gas speeds and $f$ for area (ft.$^2$). Subscripts are used to describe different stations in the engine—*see* Fig. 1.

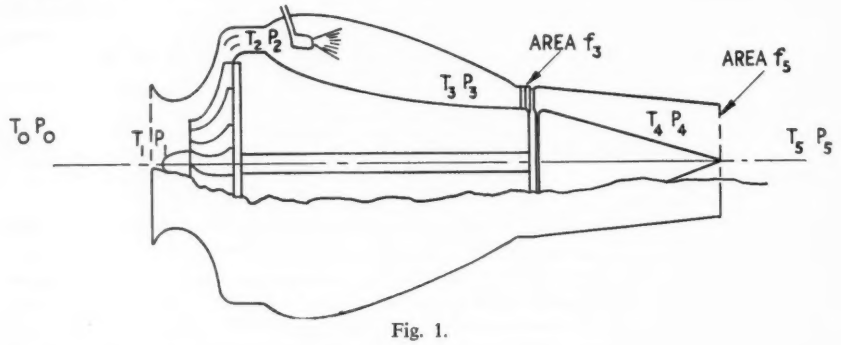


Fig. 1.

Mr. Lush's expression was

$$Y=(V/X)\,dX/dV. \quad . \quad . \quad . \quad . \quad . \quad (1)$$

From momentum considerations, the thrust of a jet engine can be expressed as

$$X=(A/g)\,(1.015v_5-V)+f_5\,(P_5-P_0). \quad . \quad . \quad . \quad (2)$$

(The constant 1.015 makes allowance for the average value of the additional mass of the fuel which is burnt.)

The last term comes into play only when the flow through the propulsive nozzle becomes supersonic; under subsonic conditions $P_5=P_0$ and the term vanishes.

For the variation of the air mass flow through the engine, the examination will be restricted to conditions of engine speed, such that sonic relations may be assumed to exist through the turbine nozzle guide vanes without introducing appreciable error. This applies on very nearly all present engines down to half-thrust conditions at least, and usually considerably below. (N.B.—Ram pressure ratios also influence matters.)

Hence

$$A=\lambda f_3 P_2/\sqrt{T_3}. \quad . \quad . \quad . \quad . \quad . \quad (3)$$

(The value of $\lambda$ is approximately 0.37 in self-consistent units.)

Moreover, the blower pressure ratio may be expressed as

$$\frac{P_2}{P_1} = \left\{1 + \frac{\theta N^2}{T_1}\right\}^{\frac{\gamma}{\gamma-1}} \; ; \; \frac{P_1}{P_0} = \left\{1 + \frac{\xi V^2}{T_0}\right\}^{\frac{\gamma}{\gamma-1}}$$

where $\theta$ and $\xi$ are constants.

Therefore

$$\frac{P_2}{P_0} = \left\{1 + \frac{\xi V^2}{T_0} + \frac{\theta N^2}{T_0}\right\}^{\frac{\gamma}{\gamma-1}} \quad . \quad . \quad . \quad . \quad (4)$$

*Sonic flow in propulsive nozzle*

Differentiate now between the case of sonic flow in the propulsive nozzle and subsonic conditions. Considering the former case, it follows from general laws that the values of $T_3$ and $v_5$ are independent of the aircraft velocity $V$, and the ratio $P_5/P_0 = kP_1/P_0$. The constant $k$ will have a fractional value unless sonic flow is encountered in the propulsion nozzle under high r.p.m. conditions at zero forward speed. This is not generally the case.

From equations (1), (2), (3) and (4) an expression for $Y$ may be obtained by suitable arrangement and simple differentiation:—

$$Y = \frac{\frac{1}{T_0}\left[\frac{\lambda}{g}\left\{\left(1 + \frac{\theta N^2}{T_0} + \frac{\xi V^2}{T_0}\right)^{\frac{1}{\gamma-1}} \frac{2\xi V^2\gamma}{\gamma-1}(1.015v_5 - V) - \right.\right.}{\left\{1 + \frac{\theta N^2}{T_0} + \frac{\xi V^2}{T_0}\right\}^{\frac{\gamma}{\gamma-1}} \frac{\lambda}{g}(1.015v_5 - V) + \frac{f_5}{f_3} T_3^{\frac{1}{2}} \left\{k\frac{P_1}{P_0} - 1\right\}}$$

$$\left. \left. - T_0 V\left(1 + \frac{\theta N^2}{T_0} + \frac{\xi V^2}{T_0}\right)^{\frac{\gamma}{\gamma-1}}\right\} + \frac{2\xi V^2\gamma}{\gamma-1} T_3^{\frac{1}{2}} \frac{f_5}{f_3} k\left(\frac{P_1}{P_0}\right)^{\frac{1}{\gamma}}\right] \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

(It should be noted that $P_2/P_0$ and $P_1/P_0$ are variables and the respective functions have been differentiated with respect to $V$.)

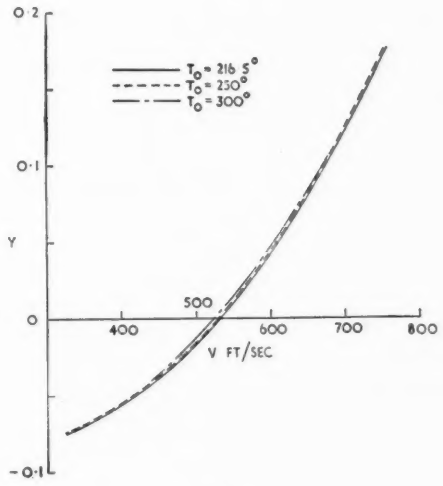


Fig. 2.

This expression is solely dependent, with respect to changes in height, on the temperature $T_0$ and not on pressures. It is too complex to appreciate as it stands and curves have been drawn (in Fig. 2) for three specific cases. It will be seen that all the curves lie very closely together although this is not obvious from the equation (5). It should be noted that in the calculations constant engine speed (maximum) operation has been assumed. A family of curves could be plotted for different engine speeds, and then it would be necessary to know the relationship between aircraft velocity in level flight and engine speed to select the correct parameter to use.

*Subsonic flow*

In this case the last term of equation (2) may be neglected. Substituting from (3) and differentiating:—

$$Y=\frac{V}{P_2}\frac{\partial P_2}{\partial V}-\frac{V}{2T_3}\frac{\partial T_3}{\partial V}+\frac{V}{1.015v_5-V}\left(1.015\frac{\partial v_5}{\partial V}-1\right) \quad . \quad . \quad (6)$$

Unfortunately it is not possible to show within the confines of this letter how this expression will vary because all three of the terms in the equation are of the same order of magnitude and great accuracy is required in the individual terms if the resultant figure, which is a difference, is not to be very inaccurate.

**O. N. LAWRENCE,** *Associate Fellow.*

I would like to thank Mr. Lawrence for his congratulations and also to offer congratulations myself to the printers for printing his equation (5).

As my paper was concerned with the reactions of engine characteristics on the behaviour of the aircraft I thought it proper to omit from it any examination of the mechanism of these characteristics. I am interested in the latter subject, but it only concerns me because any theory which would lead to reliable generalisations about $Y$ and the variation of $Y$ and net thrust with engine speed would be of great value in performance testing jet aircraft. I am particularly concerned with the climb case, when high air mass flow is combined with a relatively low air speed. Can Mr. Lawrence help here?

It would seem that in deducing equation (5) it has been assumed that intake and compressor efficiencies are independent of air speed. Is this assumption generally applicable? Also, if allowance is to be made for fuel mass flow in the exhaust is it permissible to neglect cooling drag?

**K. J. LUSH**

# an appreciation

THE COUNCIL OF THE ROYAL AERONAUTICAL SOCIETY WISH TO THANK THOSE COMPANIES WHO, BY THEIR GENEROUS CO-OPERATION, HAVE DONE SO MUCH TO HELP IN THE PRODUCTION OF THE JOURNAL


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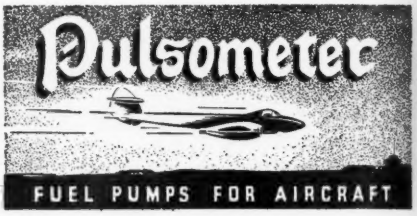


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# GRADUATES' AND STUDENTS' SECTION

*April* 1951

## ENGINEERING TRAINING IN AN AMERICAN INSTITUTE OF TECHNOLOGY, by E. J. Catchpole, B.Sc., Grad.R.Ae.S., T.M.I.Ae.S.

There has been considerable discussion in Great Britain recently on engineering training, and interest has been shown in the provision of colleges similar to the Institutes of Technology in the United States. Some facts about such an institute therefore should be of interest.

Perhaps the best known American Institutes of Technology are those at Cambridge (Massachusetts) and Pasadena (California). There are a number of others including the Georgia Institute of Technology (G.I.T.) to which particular reference will be made because of the author's personal experience of this college.

G.I.T. is the third largest engineering institution in North America with approximately six thousand students, its site being a campus of 130 acres on the outskirts of Atlanta, Georgia. It is supported mainly by the State of Georgia, which allocates roughly three million dollars per annum to its upkeep, although it has also a small endowment fund and is helped considerably with provision of plant by industry and other bodies. The Institute is divided into a number of schools or departments which include those of Aeronautical, Ceramic, Chemical, Civil, Electrical, Industrial, Mechanical and Textile Engineering, together with Chemistry, Physics, Mathematics, Mechanics, Architecture and Industrial Management. It is a noteworthy point that in June 1950, G.I.T. graduated well over three hundred students in Industrial Management alone; this is approximately four times the total annual output in Great Britain of men with a university training in management.

The School of Aeronautics was established in 1930 through a gift of three hundred thousand dollars from the Daniel Guggenheim Fund for the Promotion of Aeronautics and is one of six established in this manner. The school is housed in two buildings, a three-storey permanent structure and a single storey temporary annex. The principal building contains, in addition to air-conditioned classrooms and offices, a 9 ft. wind tunnel, a 2½ ft. tunnel, a photographic room, a large drafting room and a library. The annex houses a well equipped workshop (used mainly for building wind tunnel models, new apparatus, and such like), a small blow-down supersonic tunnel, a 20 ft. long water channel (for compressible fluid flow experiments using the hydraulic analogy) and various smaller items of test equipment. The school has a full-time instructional staff of about 10, most of whom hold advanced degrees.

The library contains some 5,000 books and 10,000 reports on aeronautical and allied subjects and is completely indexed. Its facilities are additional to those of the main Institute library of 100,000 volumes.

Most undergraduate instruction is connected with the 2½ ft. low speed wind tunnel, while the 9 ft. tunnel (recently improved with a new 50,000 dollar balance, believed to be the most accurate of its size in the U.S.) is available for graduate work. In addition, the latter tunnel is used for the considerable amount of research work which is done for government departments and aircraft companies. Advanced and graduate students are employed on research projects, wherever possible, to give them direct experience and training in such work. As an example of this, the writer was engaged for some time in assisting in an N.A.C.A.-sponsored research programme involving a number of model helicopter rotors, for which the whole experimental set-up was designed and built in the school. Although it has proved a useful piece of apparatus for thesis projects in the past, the present supersonic

[P.T.O.

tunnel is considered to be much too small for future needs. A further tunnel comparable with the more substantial ones available at other engineering institutions in the U.S. is planned.

About 200 undergraduate and 20 graduate students are enrolled at present in the School of Aeronautics. The first two years of the four-year undergraduate curriculum are spent in other departments (*e.g.* Mathematics, Mechanics, etc.) and these other departments are also used for non-aeronautical subjects in the last two years. Throughout the course, a considerable choice of subjects is allowed, both in and out of the aeronautical school. Noteworthy among the undergraduate subjects offered is the design course, which occupies nine hours per week for a year and at present involves a fairly complete design study of a racing aircraft which, it is hoped, will be built and entered for the Goodyear Trophy.

The equipment and facilities of the Institute, in aeronautical engineering and in other fields, are impressive, but it must be remembered that there are several other comparable institutes in the U.S. and some which surpass it. Financially it considers itself a "poor" school.

No attempt will be made here to draw comparisons with conditions in British technical colleges—such comparisons are left to the reader. However, one point concerning the large institute of technology is perhaps of note. There is no reason for it to become a mere machine for turning out stereotyped technicians. In fact, perhaps the greatest advantage of such an institute is the opportunity which it affords for the provision of expensive equipment and specialised instruction covering a wide range of subjects, thus making possible higher standards of training and greater flexibility to meet the changing needs of industry.

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